University of Colorado
Boulder

ECEA 5715 Power Electronics Capstone Project
Milestone 1

Kai I. Tam

January 23, 2022

1. Approach

Make a screen shot of your LTspice circuit, and paste it into the field below. Add a few sentences describing your converter approach, and how it is able to operate at point 1 (supply USB at 5 V), point 2 (supply USB at 20 V), and point 3 (charge battery), all with the same three-cell LiPo battery. The battery ground and USB ground should be connected. The schematic screen shot should include only your circuit—it is not necessary to include the header part provided in milestone1.asc (simulation commands and parameters, control signals, battery and bus models, measurement commands).

Figure 1. Non-inverting Buck Boost Converter

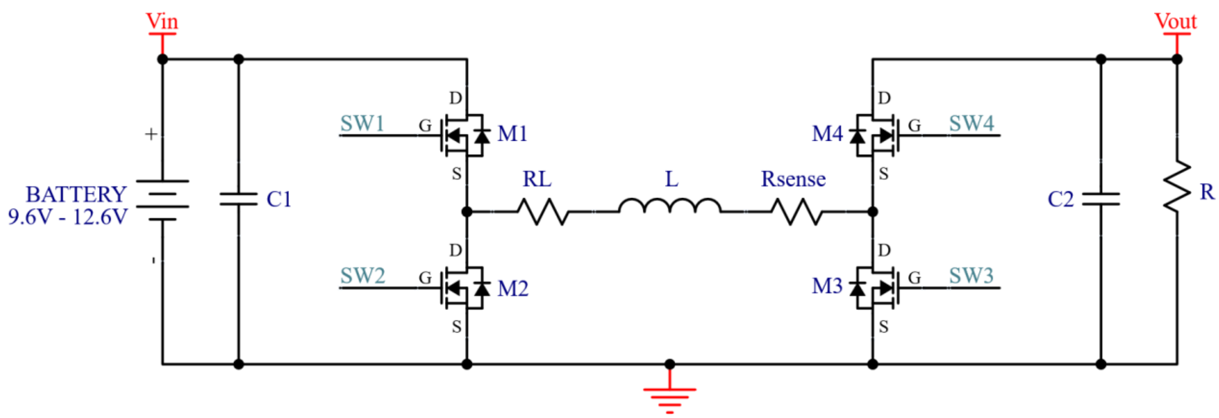


Figure 2. Bidirectional Non-inverting Buck Boost Converter

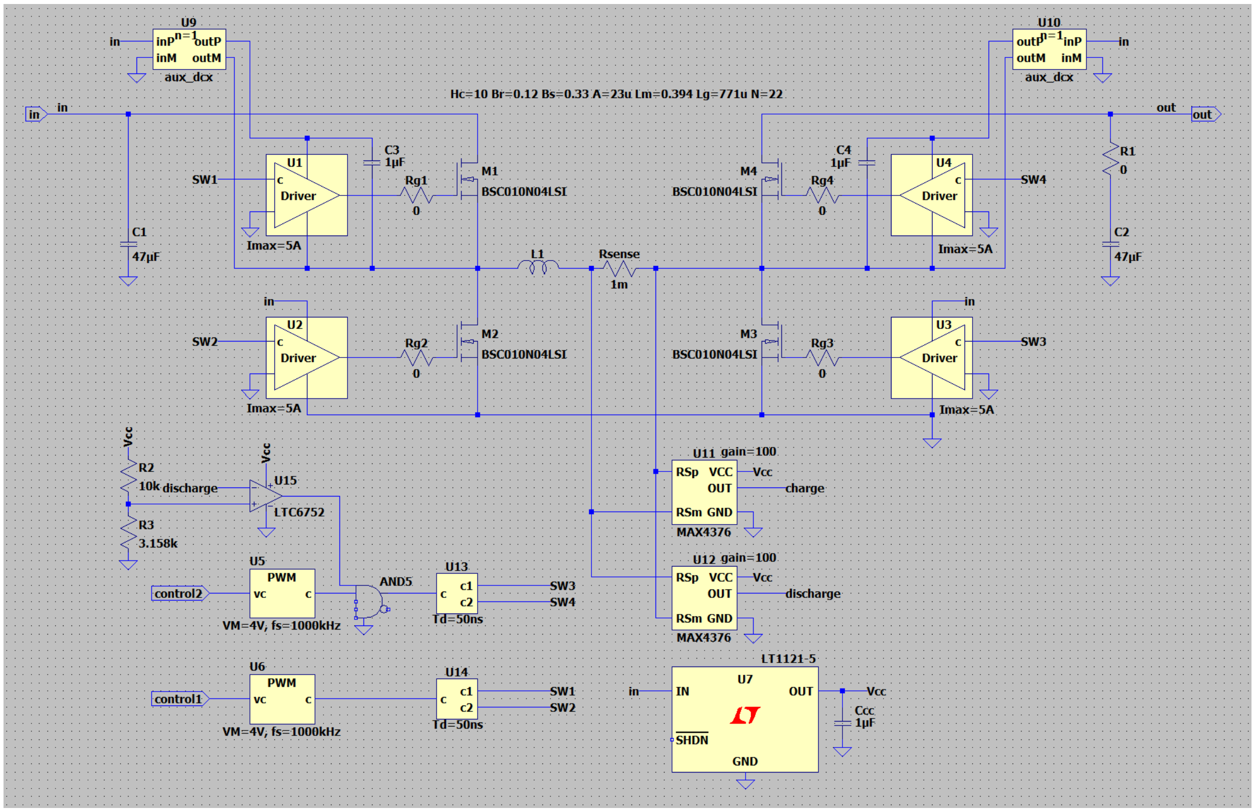


Figure 3. LTSpice Schematic.

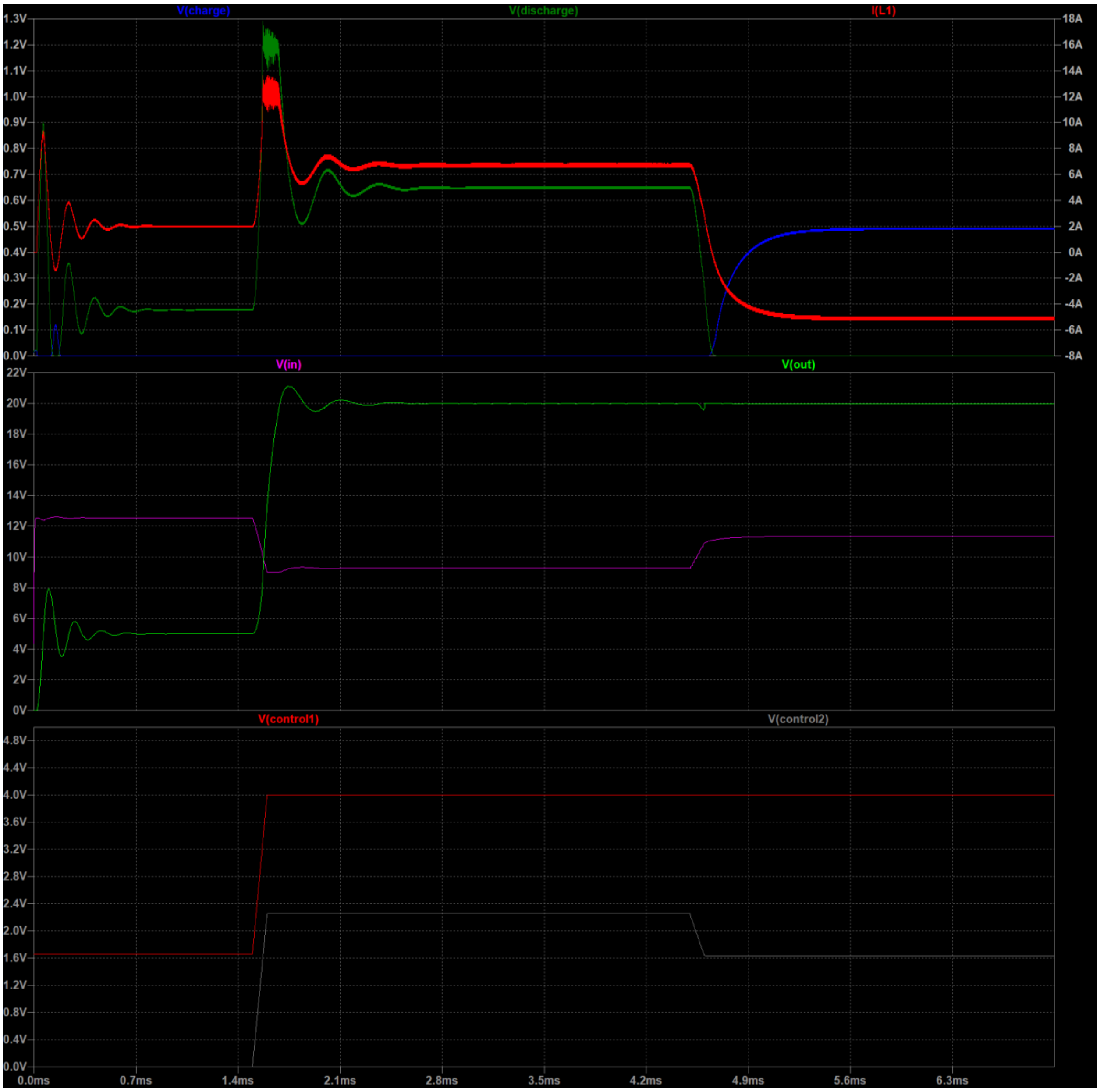


Figure 4. LTSpice plot

Point1 Buck Mode

<Description here>

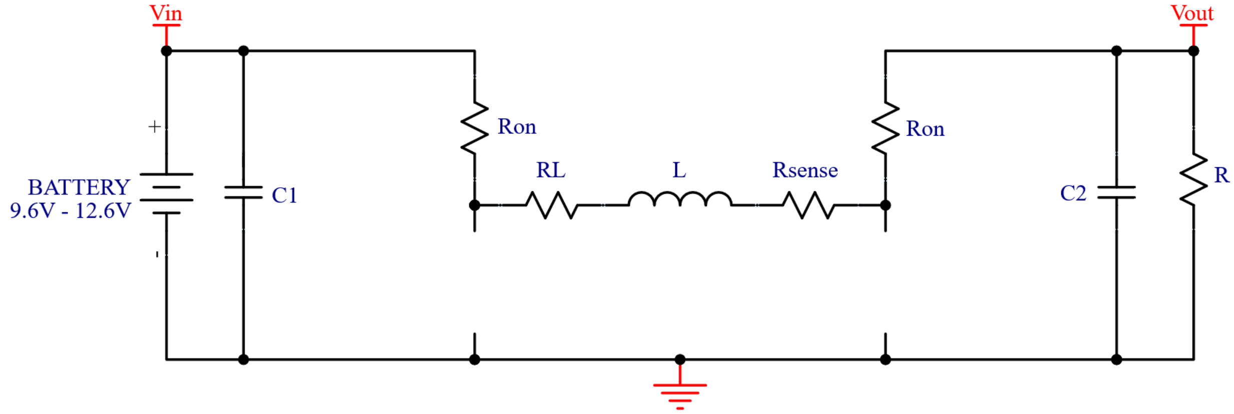


Figure 5. Point1 Buck Mode (D)

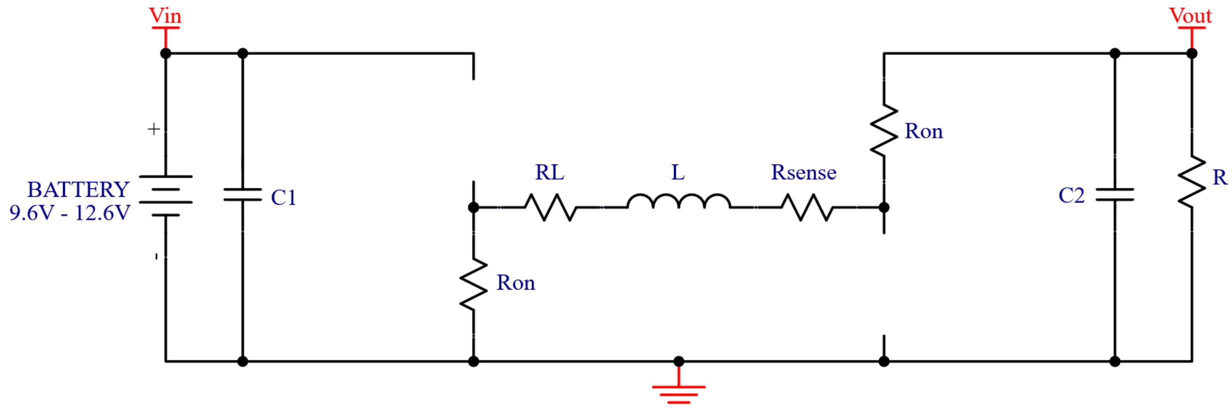


Figure 6. Point1 Buck Mode (1-D)

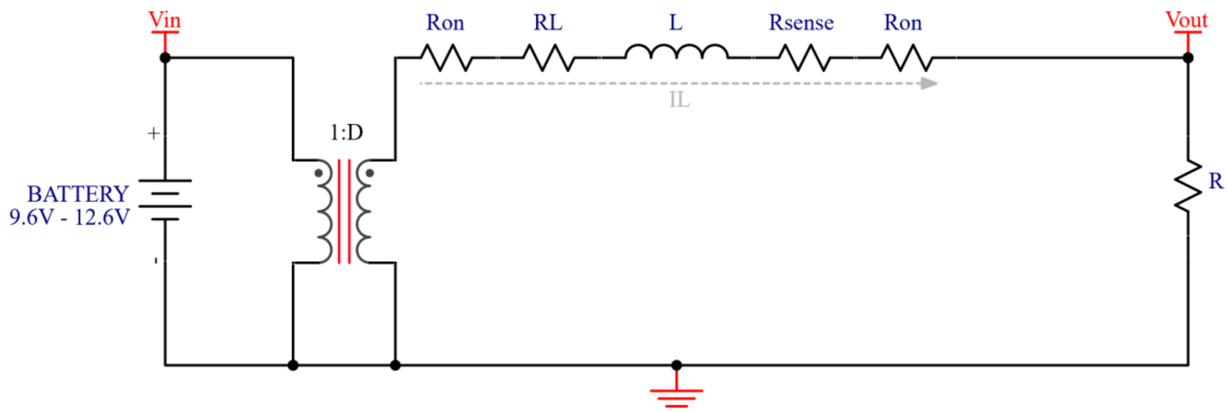


Figure 7. Equivalent Model of Point1 Buck Mode

Voltage-Sec Balance

$$< V_L >_{Ts} = D(V_{in} - I_L(2R_{on} + R_L + R_{sense}) - V_{out}) + D'(-V_{out} - I_L(2R_{on} + R_L + R_{sense})) = 0$$

$$DV_{in} - DV_{out} - D'V_{out} - I_L(2R_{on} + R_L + R_{sense}) = 0$$

$$\boldsymbol{V_{out} = DV_{in} - I_L(2R_{on} + R_L + R_{sense})}$$

Charge Balance

$$< I_{C2} >_{Ts} = I_L - \frac{V_{out}}{R} = 0$$

$$I_L = \frac{V_{out}}{R} = \frac{DV_{in} - I_L(2R_{on} + R_L + R_{sense})}{R}$$

$$DV_{in} = I_L R + I_L(2R_{on} + R_L + R_{sense})$$

$$\boldsymbol{I_L = \frac{DV_{in}}{R + (2R_{on} + R_L + R_{sense})} = I_{out}}$$

Eliminate IL

$$V_{out} = DV_{in} - I_L(2R_{on} + R_L + R_{sense})$$

$$V_{out} = DV_{in} - I_{out}(2R_{on} + R_L + R_{sense})$$

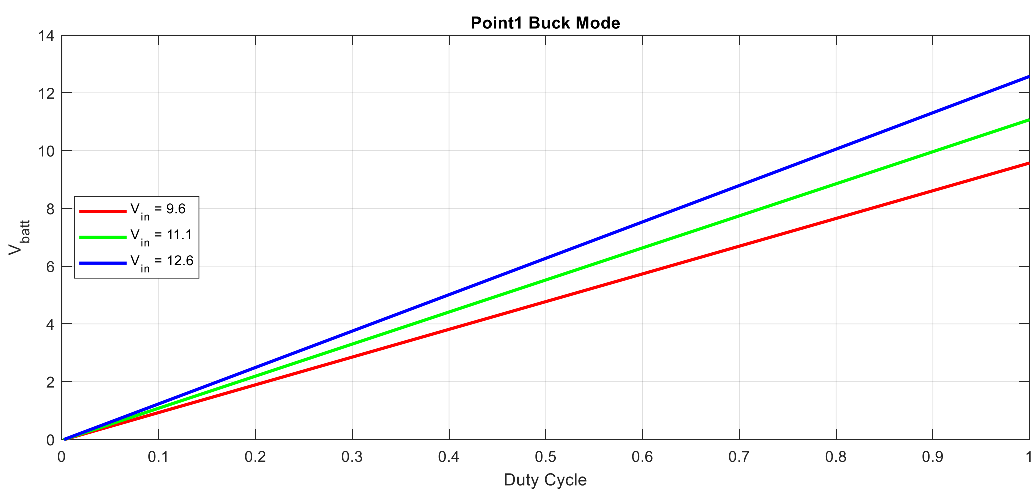
$$\boldsymbol{D = \frac{V_{out} + I_{out}(2R_{on} + R_L + R_{sense})}{V_{in}}}$$

	Vin	Direction	Vout	Topology	Vcontrol1	Vcontrol2
	V		V		Duty Cycle	Duty Cycle
Point 1	12.6	→	5	Buck	0.5238	0
	11.1				0.453	
	9.6				0.3991	

```
clear all;
%%%%% Point1 Buck Mode %%%%%

%%%%% Given Parameters %%%%%
V_in_low = 9.6;
V_in_mid = 11.1;
V_in_high = 12.6;

R_on = 1.05e-03;
R_L = 10e-03;
R_sense = 2e-03;
R_lost = 2*R_on + R_L + R_sense;

%%%%% Output Current %%%%%
I_out = 2;

%%%%% Duty Cycle Plot Resolution %%%%%
d = 0:0.0001:1;

%%%%% Vout Formula with Three Different Input %%%%%
V_out_low = d*V_in_low-(I_out)*(R_lost);
V_out_mid = d*V_in_mid-(I_out)*(R_lost);
V_out_high = d*V_in_high-(I_out)*(R_lost);

%%%%% Plot Settings %%%%%
plot(d,V_out_low,'r', d,V_out_mid,'g', d,V_out_high,'b')

title('Point1 Buck Mode');
xlabel('Duty Cycle');
ylabel('V_b_a_t_t');
axis([0 1 0 14])
legend({'V_i_n = 9.6','V_i_n = 11.1','V_i_n = 12.6'},'Location','west');
grid on;
h = findobj(gcf,'type','line');
set(h,'LineWidth',2);

Duty_low = interp1(V_out_low, d, 5);
Duty_mid = interp1(V_out_mid, d, 5);
Duty_high = interp1(V_out_high, d, 5);
fprintf('Duty Cycle at Vin = 12.6V, Vout = 5V is %1.4f\n', Duty_low);
fprintf('Duty Cycle at Vin = 11.1V, Vout = 5V is %1.4f\n', Duty_mid);
fprintf('Duty Cycle at Vin = 9.6V, Vout = 5V is %1.4f\n', Duty_high);
```

MATLAB 1. Point1 Buck Mode

```
Duty Cycle at Vin = 12.6V, Vout = 5V is 0.5238
Duty Cycle at Vin = 11.1V, Vout = 5V is 0.4530
Duty Cycle at Vin = 9.6V, Vout = 5V is 0.3991
```



Point2 Boost Mode

<Description here>

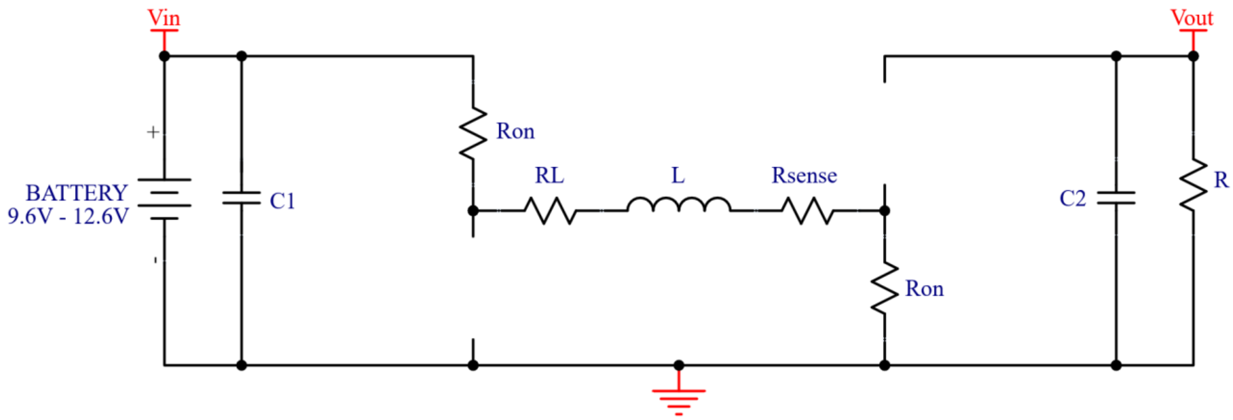


Figure 5. Point2 Boost Mode (D)

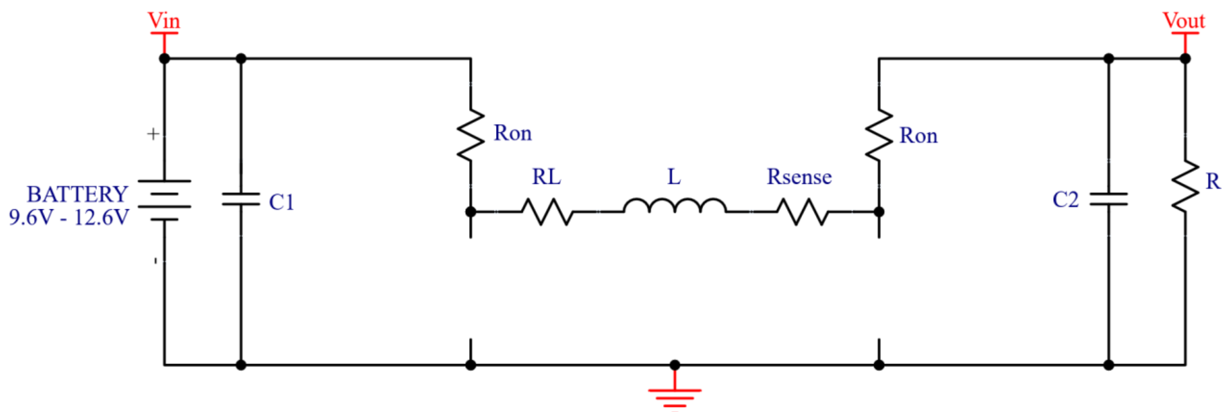


Figure 6. Point2 Boost Mode (1-D)

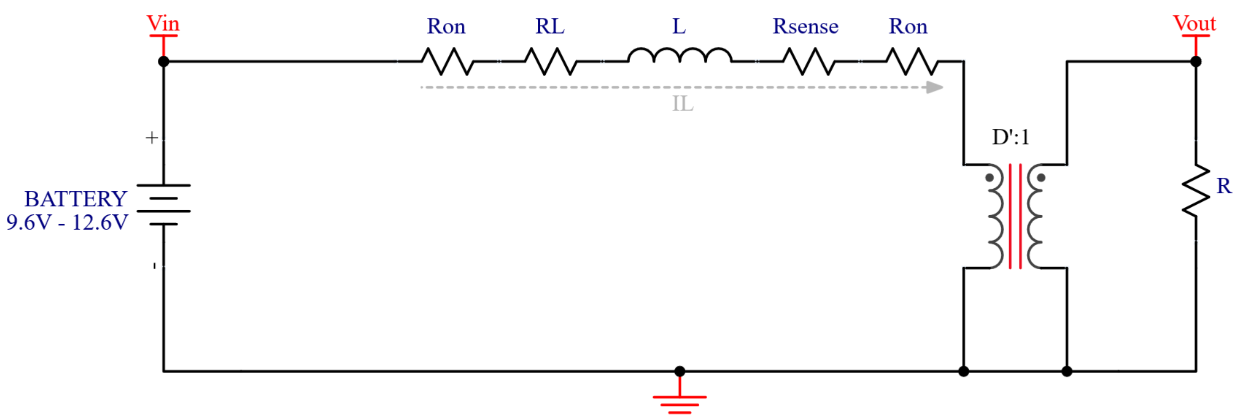


Figure 7. Equivalent Model of Point2 Boost Mode

Voltage-Sec Balance

$$< V_L >_{Ts} = D\big(V_{in} - I_L(2R_{on} + R_L + R_{sense})\big) + D'(V_{in} - V_{out} - I_L(2R_{on} + R_L + R_{sense})) = 0$$

$$V_{in} - D'V_{out} - I_L(2R_{on} + R_L + R_{sense}) = 0$$

$$\boldsymbol{V_{out} = \frac{V_{in}}{D'} - \frac{I_L}{D'}(2R_{on} + R_L + R_{sense})}$$

Charge Balance

$$< I_{C2} >_{Ts} = D\left(-\frac{V_{out}}{R}\right) + D'\left(I_L - \frac{V_{out}}{R}\right) = 0$$

$$D'I_L - \frac{V_{out}}{R} = 0$$

$$\boldsymbol{I_L = (\frac{1}{D'})\frac{V_{out}}{R}}$$

Eliminate IL

$$V_{out} = \frac{V_{in}}{D'} - \frac{1}{D'^2}(\frac{V_{out}}{R})(2R_{on} + R_L + R_{sense})$$

$$V_{out} + \frac{1}{D'^2}(\frac{V_{out}}{R})(2R_{on} + R_L + R_{sense}) = \frac{V_{in}}{D'}$$

$$V_{out}(1 + \frac{2R_{on} + R_L + R_{sense}}{D'^2 R}) = \frac{V_{in}}{D'}$$

$$\boldsymbol{V_{out} = \frac{V_{in}}{D'} \cdot (\frac{1}{1 + \frac{2R_{on} + R_L + R_{sense}}{D'^2 R}})}$$

	Vin	Direction	Vout	Topology	Vcontrol1	Vcontrol2
	V		V		Duty Cycle	Duty Cycle
Point 2	12.6	→	20	Boost	0	0.3724
	11.1					0.4477
	9.6					0.5231

```
clear all;
%%%%% Point2 Boost Mode %%%%%

%%%%% Given Parameters %%%%%
V_in_low = 9.6;
V_in_mid = 11.1;
V_in_high = 12.6;

R_on = 1.05e-03;
R_L = 10e-03;
R_sense = 2e-03;
R = 30/3;
R_lost = 2*R_on + R_L + R_sense;

%%%%% Output Current %%%%%
I_out = 3;

%%%%% Duty Cycle Plot Resolution %%%%%
d = 0:0.0001:1;

%%%%% Vout Formula with Three Different Input %%%%%
V_out_low = (1./(1-d))*V_in_low.*(1./(1+R_lost./(((1-d).^2)*R)));
V_out_mid = (1./(1-d))*V_in_mid.*(1./(1+R_lost./(((1-d).^2)*R)));
V_out_high = (1./(1-d))*V_in_high.*(1./(1+R_lost./(((1-d).^2)*R)));

%%%%% Plot Settings %%%%%
plot(d,V_out_low,'r', d,V_out_mid,'g', d,V_out_high,'b')

title('Point2 Boost Mode');
xlabel('Duty Cycle');
ylabel('V_b_a_t_t');
axis([0 1 0 180])
legend({'V_i_n = 9.6','V_i_n = 11.1','V_i_n = 12.6'},'Location','west');
grid on;
h = findobj(gcf,'type','line');
set(h,'LineWidth',2);
```

MATLAB 2. Point2 Boost Mode

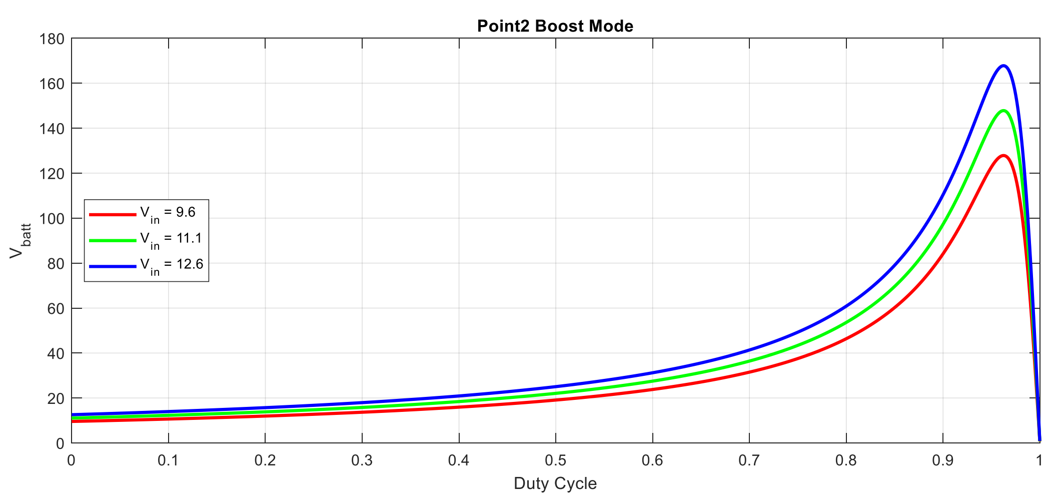


Figure 8. Point2 Boost Mode

Reverse Buck Charging Mode

When in Charging Mode, we will turn the H-bridge to a Buck Mode converter, by using SW4 as the main switch, SW3 as a synchronize circulating path at (1-D), SW1 will be turn on constantly and SW2 will be constantly OPEN. Where Vcontrol2 will be used to control the duty cycle of SW4.

Here we rename the following to avoid confusion:

$$V_{in} = V_{batt}$$
$$V_{out} = V_{bus}$$

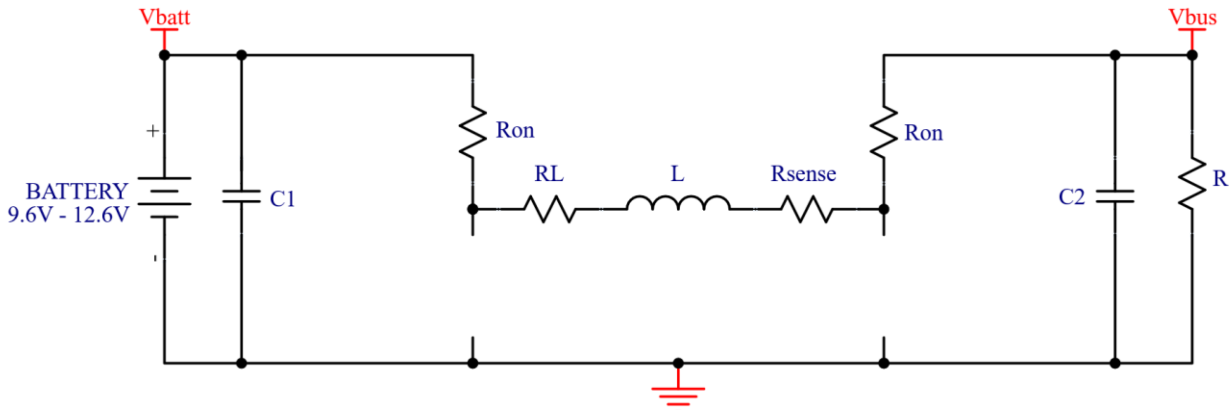


Figure 10. Reverse Buck Charging Mode (D)

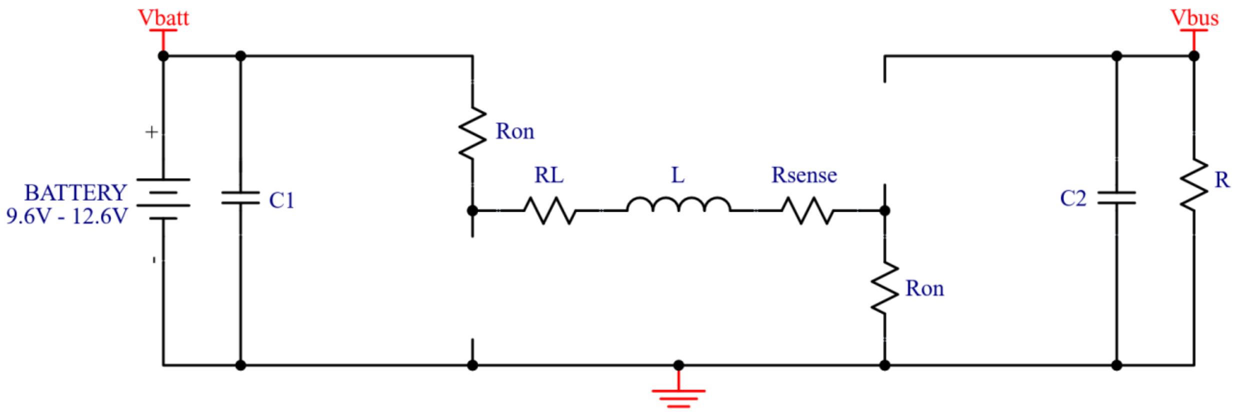


Figure 11. Reverse Buck Charging Mode (1-D)

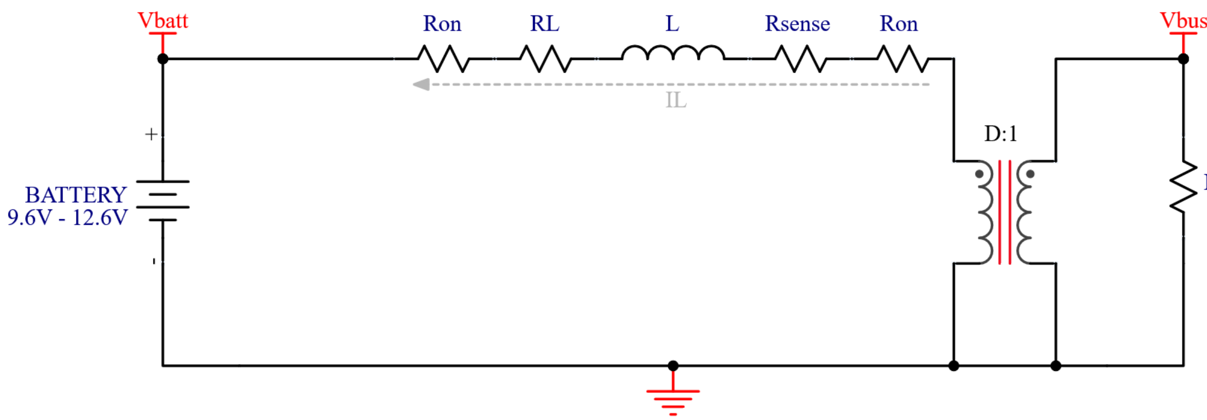


Figure 12. Reverse Buck Charging Mode (1-D)

Voltage-Sec Balance

$$< V_L >_{Ts} = D(V_{bus} - I_L(2R_{on} + R_L + R_{sense}) - V_{batt}) + D'\left(-V_{batt} - I_L(2R_{on} + R_L + R_{sense})\right) = 0$$

$$DV_{bus} - DV_{batt} - D'V_{batt} - I_L(2R_{on} + R_L + R_{sense}) = 0$$

$$\boldsymbol{V_{batt} = DV_{bus} - I_L(2R_{on} + R_L + R_{sense})}$$

Charge Balance

$$< I_{C1} >_{Ts} = I_L - \frac{V_{batt}}{R_{batt}} = 0$$

$$I_L = \frac{V_{batt}}{R_{batt}} = \frac{DV_{bus} - I_L(2R_{on} + R_L + R_{sense})}{R_{batt}}$$

$$DV_{bus} = I_L R_{batt} + I_L(2R_{on} + R_L + R_{sense})$$

$$I_{battery\ charging} = I_L = \frac{DV_{bus}}{R_{batt} + (2R_{on} + R_L + R_{sense})}$$

Here we can observe the Inductor current will be the charging current of the Battery.

$$\boldsymbol{I_{battery\ charging} = I_L = \frac{I_{bus}}{D}}$$

Eliminate IL

$$\boldsymbol{V_{batt} = DV_{bus} - \frac{I_{bus}}{D}(2R_{on} + R_L + R_{sense})}$$

```
clear all;
%%%%% Buck Mode (Charging%%%%%

%%%%% Given Parameters %%%%%
V_bus = 20;

R_on = 1.05e-03;
R_L = 10e-03;
R_sense = 2e-03;
R_lost = 2*R_on + R_L + R_sense;

%%%%% Bus Current %%%%%
I_bus = 3;

%%%%% Duty Cycle Plot Resolution %%%%%
d = 0:0.0001:1;

%%%%% Vout Formula with Three Different Input %%%%%
V_batt = d*V_bus-(I_bus./d).*(R_lost);


%%%%% Plot Settings %%%%%
plot(d,V_batt,'k')

title('Reverse Buck Charging Mode, I_b_u_s = 3A');
xlabel('Duty Cycle');
ylabel('V_b_a_t_t');
axis([0 1 0 22])
legend({'V_b_u_s = 20'},'Location','west');
grid on;
h = findobj(gcf,'type','line');
set(h,'LineWidth',2);
```

MATLAB 3. Reverse Buck Charging Mode

	Vin	Direction	Vout	Topology	Vcontrol1	Vcontrol2
	V		V		Duty Cycle	Duty Cycle
	12.6					0.6335
Point 3	11.1	←	20	Buck	0	0.5589
	9.6					0.4845

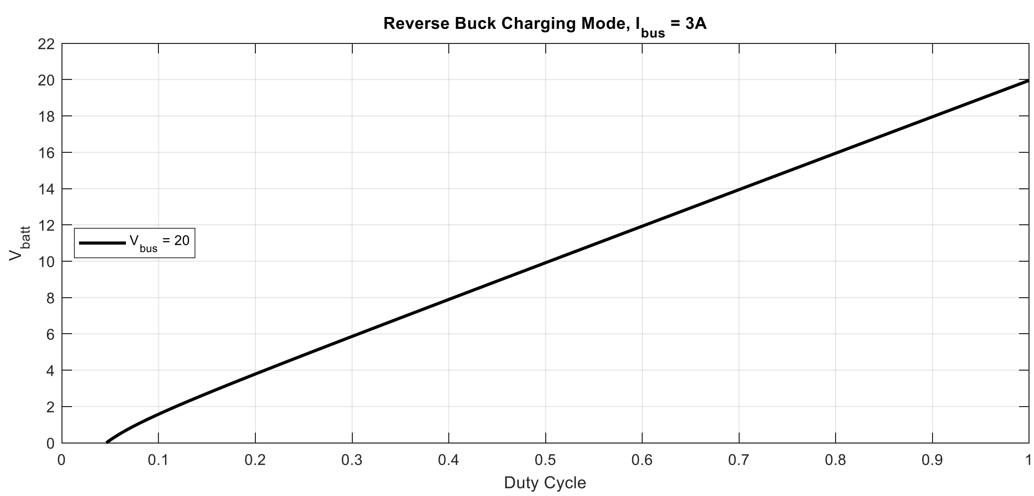


Figure 13. Reverse Buck Charging Mode, Ibus = 3A

2. Inductor Design

In the power stage, each inductor should be designed following the Kg method presented in Course 5 of this specialization. You must use a ferrite core (or ferrite cores) with core material having the following LTspice B - H loop parameters: Hc = 10, Br = 0.12, Bs = 0.33 (so the saturation flux density is approximately 0.33 Tesla). The inductors must not saturate in steady-state operation at the worst-case operating point. For each inductor in your power converter report the following:

1. Worst-case operating point for the inductor design: state Vbat, Vout, and Iout

Point 2, Vbat = 9.6V, Vout = 20V, Iout = 3A

Check IL comparison of each point in step 3 below.

2. DC value IL of the inductor current at the worst-case operating point: include equations used to calculate IL, and report IL value as a number with units.

$$I_L = \left(\frac{1}{D'}\right)\frac{V_{out}}{R} = \left(\frac{1}{1-0.5231}\right)\cdot 3 = \mathbf{6.2906A}$$

Switching Frequency = 1MHz (by choice)
Switching Period = 1/1MHz = 1µS
Maximum allowable Peak to Peak Current Ripple ≈ 5% (by choice)

$$V_L(t) = L\frac{dI_L(t)}{dt}$$

$$\Delta I_L = \frac{0.05\times I_L}{2} = \frac{0.05\times 6.2906}{2} = 158mA$$

3. Selected inductance L: include equations used to calculate L, and report inductance L as a number with units.

Minimum Desired Inductor Value that covers worst case scenario (neglect losses)

$$L = \frac{V_{in}DT_s}{2\Delta I_L} = \frac{9.6 \cdot 0.5231 \cdot 1\mu S}{2 \cdot 158mA} = \mathbf{15.96\mu H}$$

For conservative purpose, we will use a common commercial value: $\mathbf{18\mu H}$
With Inductance chosen, recalculate ripple and ILmax.

	Vin	Direction	Vout	IL	Duty	L	ts	dIL(t)	ΔIL	ILmax
	V		V	A		H	s	A	A	A
Point 1	12.6	→	5	2.0000	0.3991	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
	11.1		5	2.0000	0.453	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
	9.6		5	2.0000	0.5238	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
Point 2	12.6	→	20	4.7801	0.3724	1.80E-05	1.00E-06	0.2607	0.1303	4.9105
	11.1		20	5.4318	0.4477	1.80E-05	1.00E-06	0.2761	0.1380	5.5699
	9.6		20	6.2906	0.5231	1.80E-05	1.00E-06	0.2790	0.1395	6.4301
Point 3	20	←	12.6	4.7356	0.6335	1.80E-05	1.00E-06	0.7039	0.3519	5.0875
	20		11.1	5.3677	0.5589	1.80E-05	1.00E-06	0.6210	0.3105	5.6782
	20		9.6	6.1915	0.4845	1.80E-05	1.00E-06	0.5383	0.2692	6.4607

4. Required Kg: include equations used to calculated Kg, and report the value as a number with units.

Inductance at zero current = 18uH
Imax = 6.4301A, (we will round it to 7A)
Bmax = 0.25T
DC winding resistance R = 20mΩ (by choice)
Fill factor Ku = 0.6

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} = \frac{(1.724 \cdot 10^{-6})(18 \cdot 10^{-6})^2 (7)^2}{(0.25)^2 (0.02)(0.6)} 10^8 = \mathbf{3.6 \times 10^{-3} cm^5}$$

5. Selected core size: justify how you selected the core size, and report the selected core size. You must use cores in the magnetics design tables of standard cores provided in the course (file "AppendixD.pdf").

Core type (A) (mm)	Geometrical constant K_g (cm^5)	Geometrical constant K_{gfe} (cm^x)	Cross-sectional area A_c (cm^2)	Bobbin winding area W_A (cm^2)	Mean length per turn MLT (cm)	Magnetic path length ℓ_m (cm)	Core weight (g)
EE12	$0.731 \cdot 10^{-3}$	$0.458 \cdot 10^{-3}$	0.14	0.085	2.28	2.7	2.34
EE16	$2.02 \cdot 10^{-3}$	$0.842 \cdot 10^{-3}$	0.19	0.190	3.40	3.45	3.29
EE19	$4.07 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	0.23	0.284	3.69	3.94	4.83

6. Selected air gap lg: include equations used to calculate lg and report the value of lg as a number with units.

$$l_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 = \frac{(4 \cdot \pi \cdot 10^{-7})(18 \cdot 10^{-6})(7)^2}{(0.25)^2(0.23)} 10^4 = \mathbf{7.71 \cdot 10^{-4} m}$$

7. Selected number of turns n and wire gauge AWG: include equations used to select n and AWG and report the values as numbers.

$$n = \frac{L I_{max}}{B_{max} A_c} 10^4 = \frac{(18 \cdot 10^{-6})(7)}{(0.25)(0.23)} 10^4 = 21.913 \approx \mathbf{22\ turns}$$

$$A_w \le \frac{K_u W_A}{n} = \frac{(0.6)(0.284)}{22} = 0.00775 cm^2$$

AWG#	Bare area, 10^{-3} cm^2	Resistance, 10^{-6} Ω/cm	Diameter, cm
15	16.51	104.3	0.153
16	13.07	131.8	0.137
17	10.39	165.8	0.122
18	8.228	209.5	0.109
19	6.531	263.9	0.0948

#19 AWG

$$R_{dc} = \frac{\rho n MLT}{A_w} = \frac{(1.724 \cdot 10^{-6})(22)(3.69)}{(0.006531)} = \mathbf{16.2 m\Omega}$$

8. Predicted Bmax in steady-state operation at the worst-case operating point: include equations used to calculate Bmax, and report the value found as a number with units. Does the inductor saturate at the worst-case operating point?

$$BscaleL1 = \frac{\mu_0 n}{l_g} = \frac{(4 \cdot \pi \cdot 10^{-7})(22)}{(7.71 \cdot 10^{-4})} = 0.0342$$

```
.param BscaleL1=0.0342
```

$$B = \frac{\mu_0 n I}{l_g} = \frac{(4 \cdot \pi \cdot 10^{-7})(22)(7)}{(7.71 \cdot 10^{-4})} = \mathbf{0.2396T}$$

9. Report the total weight of the cores used in the design as a number in grams. The weights of all standard cores are listed in the magnetics design tables. Include only the weight of the ferrite, not the copper or other parts of the inductors.

The weight of EE19 is **4.83g.**

The SpiceLine for the Inductor Model 3 (Final Choice) should be:

```
Hc=10 Br=0.12 Bs=0.33 A=23u Lm=0.394 Lg=771u N=22
Rser=0.0162
```

3. Capacitor Design

In the power stage, each capacitor should be selected following the principles presented in Course 1 of this specialization. The capacitor voltage ripple at the battery and USB terminals must be no greater than 0.1 V peak-to-peak in steady-state operation at the worst-case operating point. For any internal power stage capacitors, you may make your own choice for voltage ripple. For each capacitor in your power converter report the following:

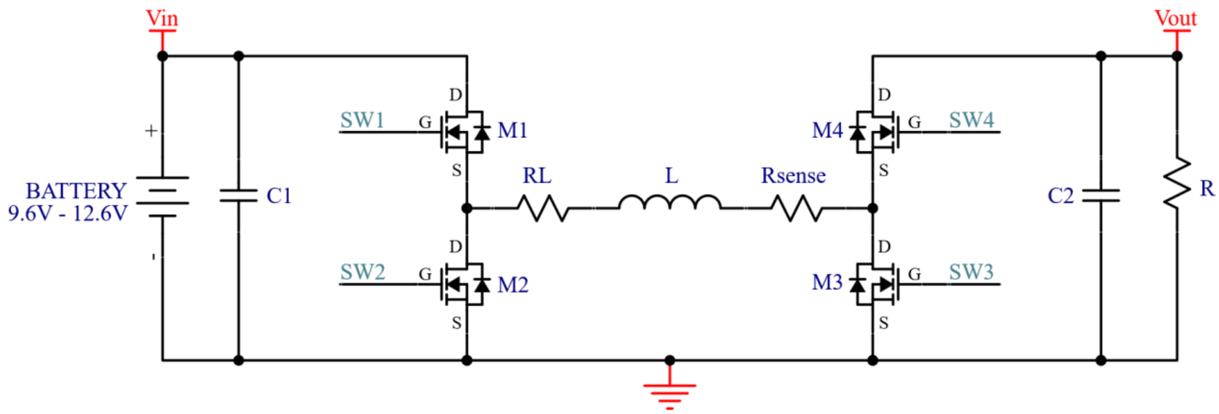


Figure 15. Bidirectional Non-inverting Buck Boost Converter

- Worst-case operating point for the capacitor design: state Vbat, Vout, and Iout

Point 2, Vbat = 9.6V, Vout = 20V, Iout = 3A
Check V ripple comparison of each point below

- Selected capacitance C: include equations used to calculate C, and report capacitance C as a number with units. For capacitors internal to the converter, report the ripple requirement that was chosen.

For Capacitor

$$I_C(t) \ = \ C\frac{dV_C(t)}{dt}$$

Maximum allowable Peak to Peak Voltage Ripple ≈ 100mV

$$\Delta V_C = 50mV$$

At Point 2, where D is at max, Ic equal to Iout at D, the minimum required Capacitor of C2 would be:

$$C_2 = \frac{I_C D T_s}{2\Delta V_C} = \frac{3 \cdot 0.5231 \cdot 1\mu S}{2 \cdot 50mV} = 15.69\mu F = \mathbf{16\mu F}$$

For conservative purpose, we will use a common commercial value: $47\mu F$

	Vin	Direction	Vout	IL	Duty	L	ts	dIL(t)	ΔIL	ILmax	Iout	C	dVc(t)	ΔVc	Vout max
	V		V	A		H	s	A	A	A	A	F	V	V	V
Point 1	12.6	→	5	2.0000	0.3991	1.80E-05	1.00E-06	0.2794	0.1397	2.1397	2	4.70E-05	0.0170	0.0085	5.0085
	11.1		5	2.0000	0.453	1.80E-05	1.00E-06	0.2794	0.1397	2.1397	2	4.70E-05	0.0193	0.0096	5.0096
	9.6		5	2.0000	0.5238	1.80E-05	1.00E-06	0.2794	0.1397	2.1397	2	4.70E-05	0.0223	0.0111	5.0111
Point 2	12.6	→	20	4.7801	0.3724	1.80E-05	1.00E-06	0.2607	0.1303	4.9105	3	4.70E-05	0.0238	0.0119	20.0119
	11.1		20	5.4318	0.4477	1.80E-05	1.00E-06	0.2761	0.1380	5.5699	3	4.70E-05	0.0286	0.0143	20.0143
	9.6		20	6.2906	0.5231	1.80E-05	1.00E-06	0.2790	0.1395	6.4301	3	4.70E-05	0.0334	0.0167	20.0167
Point 3	12.6	→	20	4.7356	0.6335	1.80E-05	1.00E-06	0.1667	0.0833	4.8189	3	4.70E-05		0.0002	20.0002
	11.1		20	5.3677	0.5589	1.80E-05	1.00E-06	0.1667	0.0833	5.4510	3	4.70E-05		0.0002	20.0002
	9.6		20	6.1920	0.4845	1.80E-05	1.00E-06	0.1667	0.0833	6.2753	3	4.70E-05		0.0002	20.0002

At Point 3 Reverse Buck Charging Mode, C1 can be served to eliminate current ripple of Inductor L.

$$\Delta v = \frac{\Delta i_L T_s}{8C_1}$$

With the current ripple of L calculated previously, minimum of C1 should be:

$$C_1 = \frac{\Delta i_{L,max} T_s}{8\Delta v} = \frac{0.3839 \cdot 2\mu S}{8 \cdot 50mV} = 1.9195\mu F$$

For Simplicity, I chose to use $10\mu F$ for the simulation. But later realize 10uF will have around 0.328V Ripple on the Input. Reason is the Battery ESR, the ripple can be roughly calculated by:

```
vin_ripple_20v: PP(v(in))=0.328175 FROM 0.00998 TO 0.01
```

$$V_{in,ripple} = Batt_{ESR} \cdot I_{in} = 0.05\Omega \cdot \frac{1}{D'} \cdot I_{out} = 0.05\Omega \cdot \frac{1}{(1-0.5231)} \cdot 3 = 0.315V$$

Choose **47uF** for C1 would bring down the ripple <0.1V to achieve the requirement.

- Report the sum of all power stage capacitances used in the design as a number in microfarads.

C1	C2	C3	C4	Ccc	Ctotal
47uF	47uF	1uF	1uF	1uF	**97uF**

4. Semiconductor Design

In the power stage, each transistor or diode should be selected following the principles presented in Course 1 of this specialization. You must use semiconductors included in the LTspice library of components. The worst-case maximum voltage applied by your converter to each semiconductor device (including switching ripple) must be no greater than 2/3 of the rated voltage of the device. For each transistor or diode in your power converter report the following:

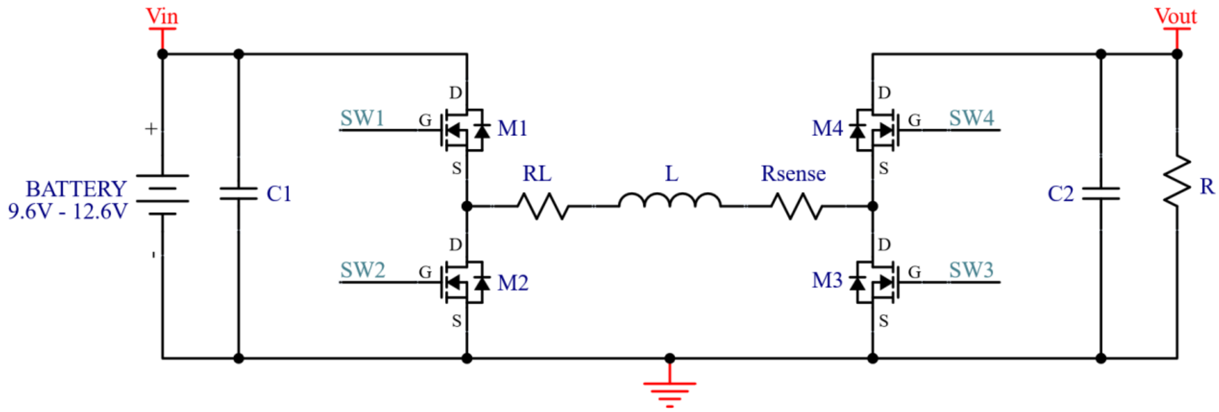


Figure 16. Bidirectional Non-inverting Buck Boost Converter

1. Worst-case operating point for the semiconductor design: state Vbat, Vout, and Iout that leads to the peak voltage reported in part 2 below.

In general, Point 2 would have the overall worst case operating point because of Max Vbat Current and Max Vout.

	Vin	Direction	Vout	IL	ΔIL	ILmax	ΔVc	Vout max
	V		V	A	A	A	V	V
Point 1	12.6	→	5	2.0000	0.1397	2.1397	0.0085	5.0085
	11.1		5	2.0000	0.1397	2.1397	0.0096	5.0096
	9.6		5	2.0000	0.1397	2.1397	0.0111	5.0111
Point 2	12.6	→	20	4.7801	0.1303	4.9105	0.0119	20.0119
	11.1		20	5.4318	0.1380	5.5699	0.0143	20.0143
	9.6		20	6.2906	0.1395	6.4301	0.0167	20.0167
Point 3	20	←	12.6	4.7356	0.0833	4.8189	0.0002	20.0002
	20		11.1	5.3677	0.0833	5.4510	0.0002	20.0002
	20		9.6	6.1920	0.0833	6.2753	0.0002	20.0002

Voltage		M1	M2	M3	M4
Point1	D		Vbat		Vout max
	D'	Vbat		Vout max	
Point2	D		Vbat		Vout max
	D'	Vbat		Vout max	
Point3	D		Vbat	Vout max	
	D'				Vout max

Voltage Worst case for M1: **Point 1**, Vbat = 12.6V, Vout = 5V, Iout = 2A
Voltage Worst case for M2: **Point 1**, Vbat = 12.6V, Vout = 5V, Iout = 2A
Voltage Worst case for M3: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A
Voltage Worst case for M4: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A

Current		M1	M2	M3	M4
Point1	D	ILmax		ILmax	
	D'		ILmax		ILmax
Point2	D	ILmax		ILmax	
	D'		ILmax		ILmax
Point3	D	ILmax			ILmax
	D'			ILmax	

Current Worst case for M1: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A
Current Worst case for M2: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A
Current Worst case for M3: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A
Current Worst case for M4: **Point 2**, Vbat = 9.6V, Vout = 20V, Iout = 3A

2. Peak applied voltage: report the maximum voltage applied by the converter to the semiconductor device (include ripple), and the required device voltage rating.

Peak applied voltage of M1: Vbat = **12.6V**
Peak applied voltage of M2: Vbat = **12.6V**
Peak applied voltage of M3: Vout max = Vout + ΔV = **20.0434V**
Peak applied voltage of M3: Vout max = Vout + ΔV = **20.0434V**

3. Selected device: report the part number that you selected, with its voltage and current ratings. For MOSFETs, also report the nominal on-resistance.

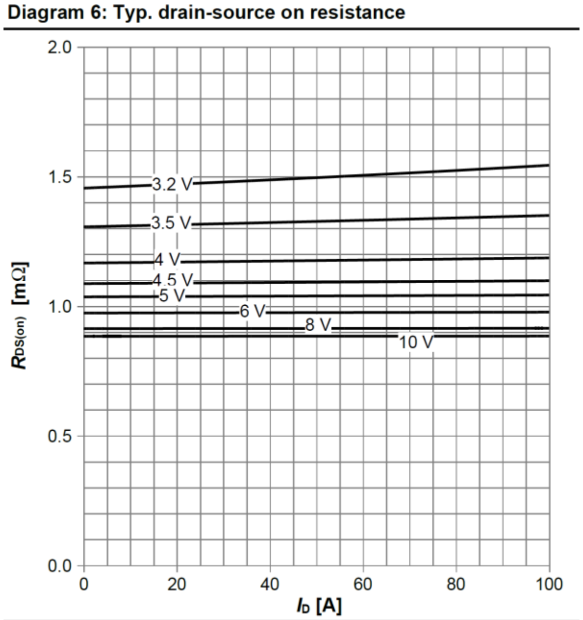
The worst-case maximum voltage applied by your converter to each semiconductor device (including switching ripple) must be no greater than 2/3 of the rated voltage of the device, I decide to pick **Infineon BSC010N04LSI**, which has Vds of 40V, 2/3 of 40V is 27V and is higher than our V peak calculated previously. And low Rsd(on) around 1.05mΩ.

https://datasheet.octopart.com/BSC010N04LSIATMA1-Infineon-datasheet-82520598.pdf

Table 1 Key Performance Parameters

Parameter	Value	Unit
V_{DS}	40	V
$R_{DS(on),max}$	1.05	mΩ
I_D	100	A
Q_{OSS}	83	nC
Q_G(0V..10V)	87	nC

Diagram 6: Typ. drain-source on resistance



$R_{DS(on)}=f(I_D)$; T_j=25 °C; parameter: V_{GS}

With our lowest Vgs (9.6V), our nominal on resistance can be as low as **0.9mΩ**
At our worst case scenario (ILmax), there would be average 63mW drop on M1 and M3

$$Power\ drop(M1, M3) \approx \left(I_{L,max}{}^2 \cdot R_{DS(on),max}\right) \cdot D = (9.6^2 \cdot 0.001) \cdot 0.6803 = 62.6964mW$$

5. Simulations

Place your LTspice files into a dedicated folder. Make sure all simulations run correctly using the files in that folder. Remove all .raw files, but include all files necessary to run the required simulations (all .sch. .asy, .lib files). Create a .zip file of the folder and upload this .zip file here.
Your LTspice files must include the Milestone1 LTspice template **milestone1.sch**, which tests your converter prototype at the three operating points:

1. USB 5V at 2A, Vbatt = 12.6V
2. USB 20V at 3A, Vbatt = 9.6V
3. Battery charging, USB 20 V at 60W, Vbatt = 11.1V

You should adjust the parameters **t1**, **t2**, and **Tend** as necessary so that the template measurements of the three operating points are made in steady state. Your simulation should use the control signal parameters **Vref1 5V**, **Vref1 20V**, etc., to set the open-loop duty cycle(s) of your converter(s) as necessary to reach the three operating points defined above, and you should adjust these parameters as well. Also define the flux density scale factor **BscaleL1** (if you have two inductors then add **BscaleL2**), and switching period parameter **Ts** so that the template produces accurate measurements.