Life Detection Module (LDM) Power Delivery PCB Project:

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Introduction:

The goal of this project is to design a power delivery system and PCB for the Life Detection Module of the uOttawa Mars Rover. The Life Detection Module is facilitates various tasks involved in collecting soil samples for future analysis. These tasks involve DC motors for drilling and for vacuuming up the soil, stepper and servo motors for positioning of the Life Detection Module “arm” during soil sample collection, and a linear actuator to extend or retract the arm at the start and end of the soil collection process. This project had some significant challenges including: high current carrying capability of the PCB, facilitating wired connections into and out of the PCB through various interconnects, ensuring proper safety features , integrating analog current sensors for current monitoring, and ofcourse the standard challenges associated with any PCB design (EMI reduction, size constraints, component and material selection, DFM requirements etc). From thorough testing, planning, design, and a few iterations: the resulting project is a power delivery system capable of providing the demands of all load devices required in the Life Detection Module.

Overview of the project:

When I was first approached by the uOttawa Mars Rover Electrical Systems subteam leader about the project, I had minimal experience with PCB design, especially for something as complex as the power delivery system for this Life Detection Module. However, I was excited to take this opportunity to stretch my skillset and expand my capabilities. I knew that this was exactly the type of challenge I was looking for in my next project. The design process began by meeting the Life Detection subteam leader to discuss the design requirements of the project, as well as stress test the max loading conditions to be expected from each of the respective motors used in the Life Detection Module. Below is a table of the stress testing current measurements and the agreed upon design specifications for each individual motor:

Table 1: Life Detection Module Motors’ respective current loads and specs for design

motor:	current testing measurements(max draw) :	spec (with tolerance)
vacuum motor	10.7A	15A
drill motor(no load)	starts(8A), continuous (2A)	N.A.
drill motor(loaded/stall torque)	40A	53A max capable, limit to 30A
linear actuator	2.3A	5A
stepper	0.25A	0.5A
servo	0.05A	0.1A

From these design specifications, along with requirements specified by both the Electrical Systems and Life Detection subteam leaders about parts inventory and coherence with other related electrical systems on the Mars Rover, the component selection process could begin. It is worth noting a few features about the system:

- The drill motor requires its own separate source from the main power delivery system's auxiliary port. Everything else is sourced from another port from the main power delivery system. That is to say, there are two input ports into this PCB.
- The drill motor, vacuum motor, and linear actuator motor must go through individual Spark motor controllers via screw terminal/XT90 connections over 12 awg gauge wire. This meant integrating screw terminals on the PCB to facilitate power delivery both into and out of the PCB at various stages in the power flow chain.
- The drill motor, vacuum motor, and linear actuator motor must go through individual analog current sensors so that the current draw of each can be monitored.This also invoked the need for header connections for communication with a microcontroller.
- A 12V-to-5V buck converter and subsequent 5V rail power supply was implemented to power the soil stepper motor, the drill/vacuum stepper motor, the soil servo motor, respective motor controllers, and the respective current sensors involved in the power delivery system. This additional power supply also invoked the associated EMI filter design at the input of the buck converter.
- Some of the design choices were dictated by preferences from both subteam leaders, including the use of XT90 connectors, the use of the Spark motor controllers, and the use of PCB standoffs for easy implementation and replacement of the stepper motor controller breakout board PCBs instead of integration of these motor controllers directly on the main PCB.

An overview of the Life Detection Module power delivery system design is shown in the block diagram below:

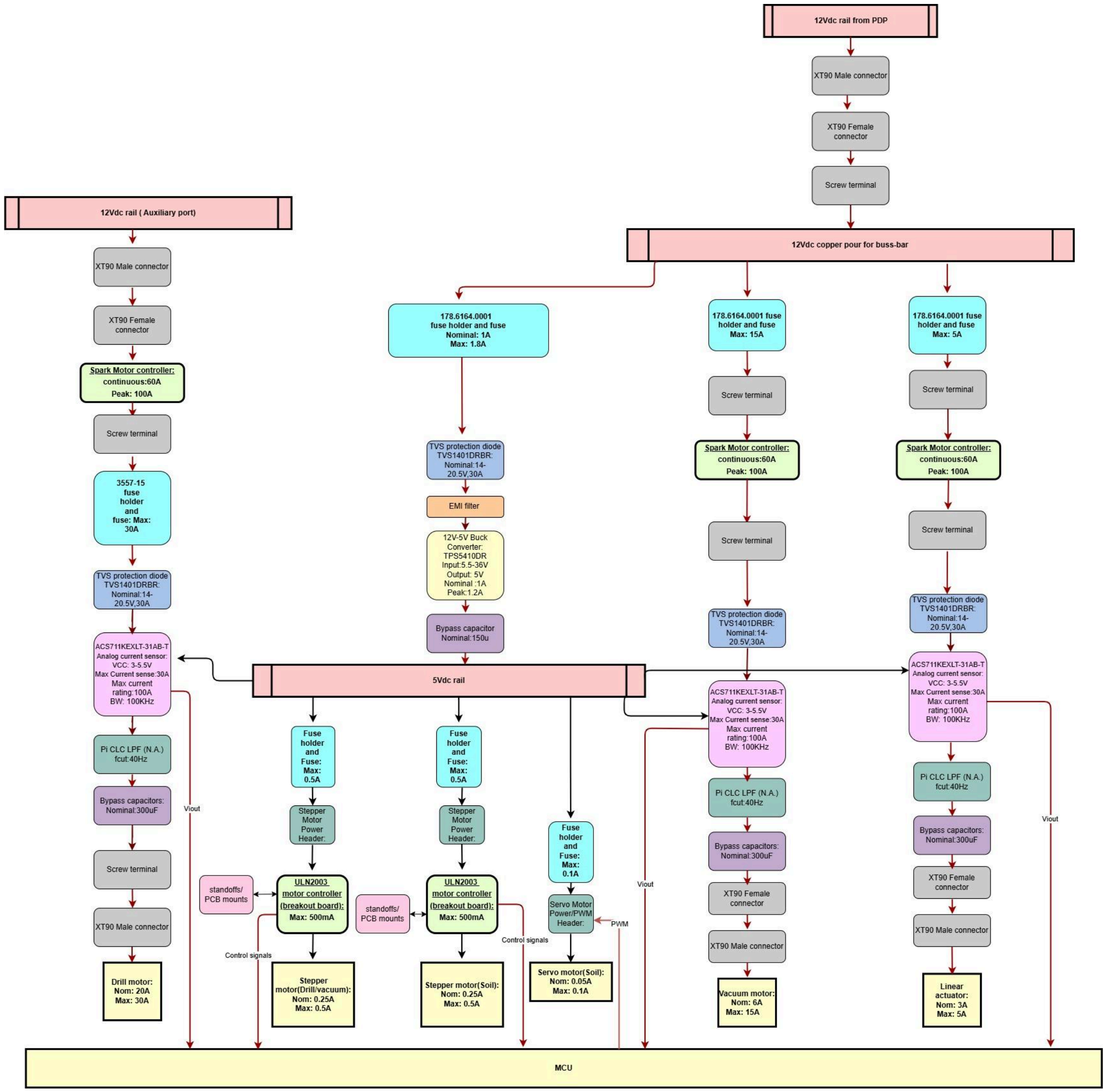


Figure 1:Block diagram of the overall LDM power delivery system

Body:

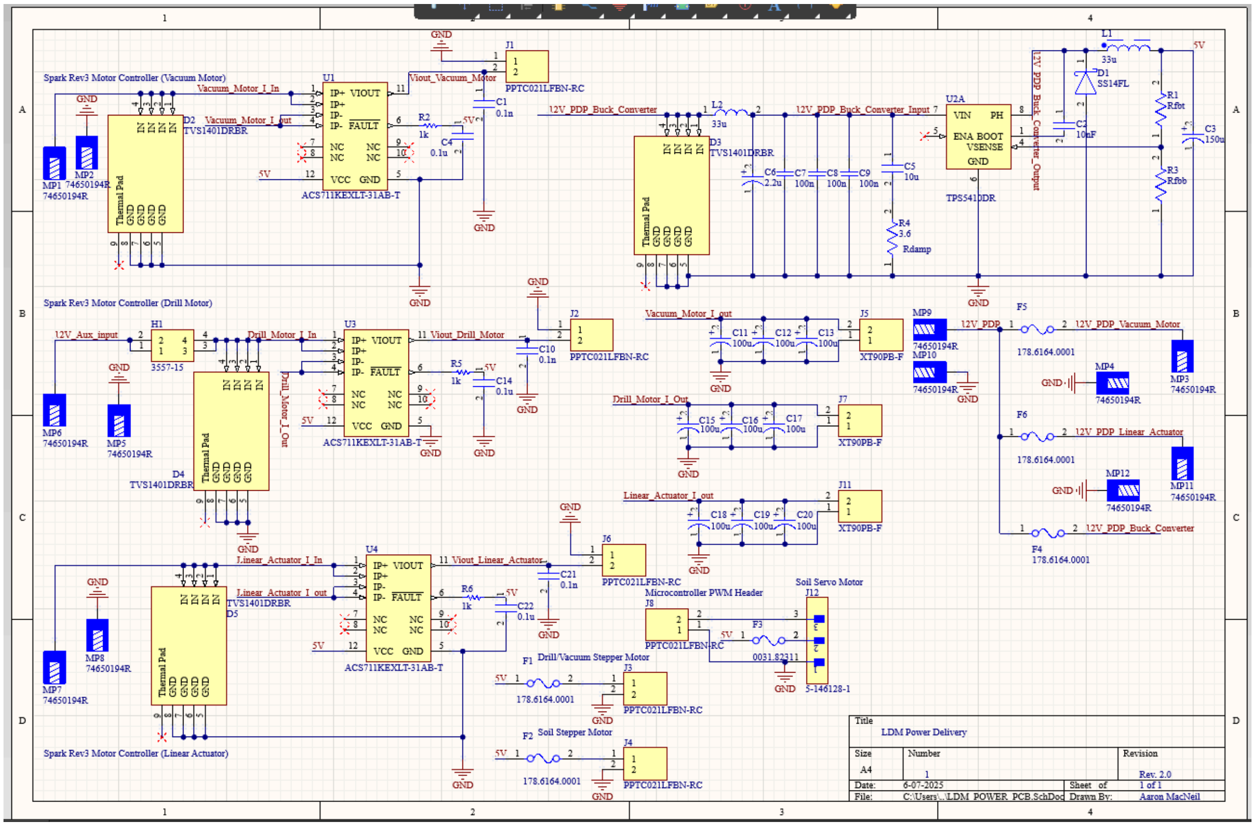


Figure 2: Schematic of the LDM power delivery PCB

#	Name	Material	Type	Weight	Thickness	Dk	Df
	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask		0.01016mm	3.8	
1	Top Layer		Signal	1oz	0.07112mm		
	Dielectric 2	PP-006	Prepreg		0.321mm	4.1	0.02
2	GND	CF-004	Plane	1oz	0.07112mm		
	Dielectric 1	FR-4	Dielectric		0.643mm	4.8	
3	PDP_Return	CF-004	Plane	1oz	0.07112mm		
	Dielectric 3	PP-006	Prepreg		0.321mm	4.1	0.02
4	PDP_Power		Signal	1oz	0.07112mm		
	PDP_Power Solder	Solder Resist	Solder Mask		0.01016mm	3.8	
	PDP_Power Over...		Overlay				

Figure 3: 4-layer stackup of the LDM power delivery PCB

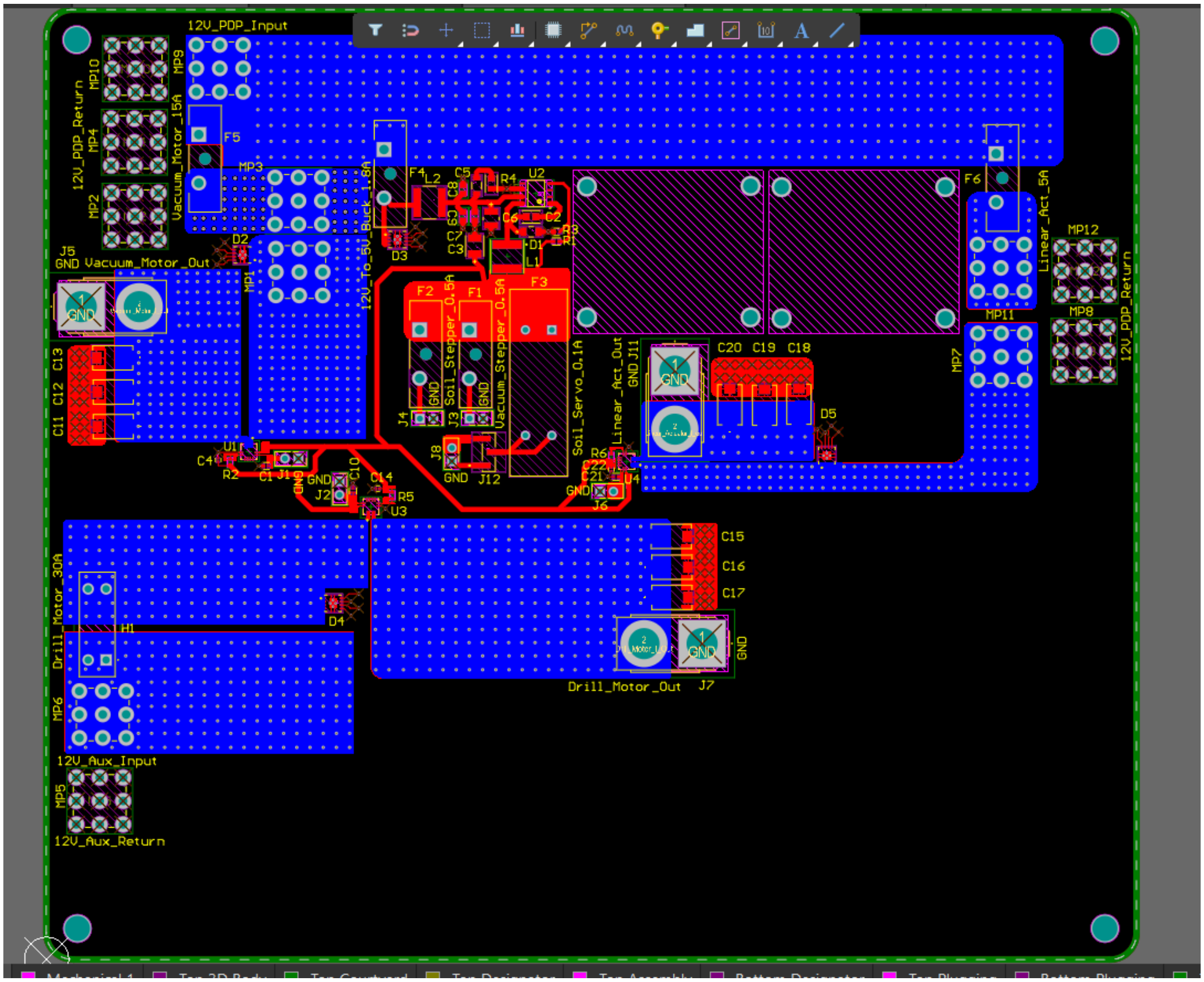


Figure 4: 2D view of the LDM power delivery PCB

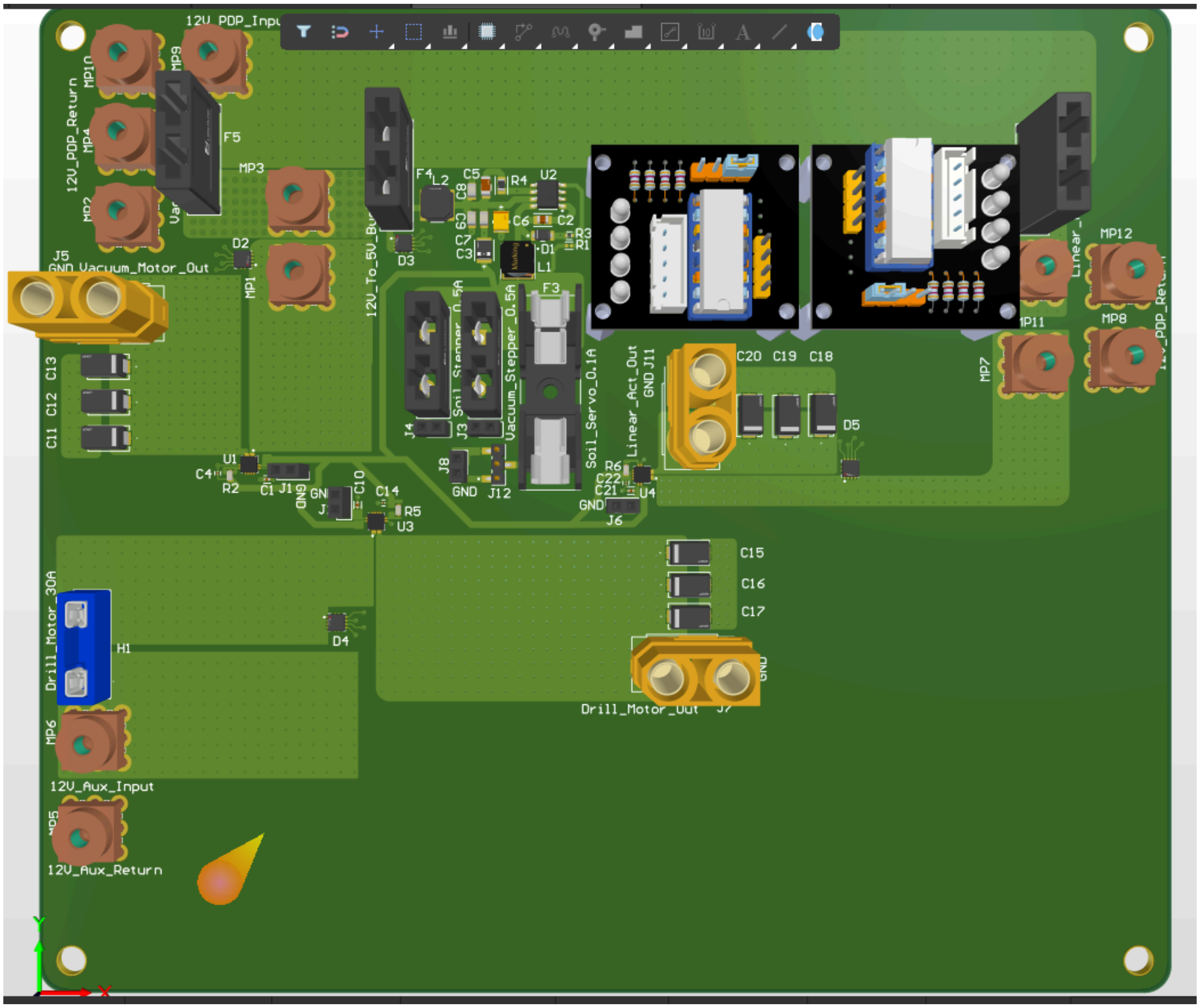


Figure 5: 3D view of the LDM power delivery PCB

Comment	Description	Designator	Footprint	LibRef	Qu
0.1n	Ceramic Capacitor for Automotive 100pF ±5% 50VDC C0G 0402 Paper T/R	C1, C10, C21	FP-GCM155-0_05-IPC_C	CMP-2008-03694-3	3
10nF	General Purpose Ceramic Capacitor, 0805, 10nF, 10%, X7R, 0.15, 50V	C2	FP-0805-L_2_01_0_2-W_1_25-IPC_A	CMP-2000-05015-2	1
150u	Molded Tantalum Polymer Capacitor 150uF 20% 6.3V life 1000Hours SMD 1411	C3	FP-POSCAP-B15G-MFG	CMP-05428-000197-1	1
0.1u	Chip Multilayer Ceramic Capacitors for General Purpose, 0201, 0.10uF, X5R, 15%, 10%, 6.3V	C4, C14, C22	FP-GRM033-0_03-MFG	CMP-06035-000062-2	3
10u	Chip Multilayer Ceramic Capacitors for General Purpose, 1206, 10uF, X7R, 15%, 10%, 25V	C5	FP-GRM31C-0_2-e0_3_0_8-MFG	CMP-06035-003589-1	1
2.2u	2.2uF 25V ±10% 4.5Ω 1210 SMD Tantalum Capacitor	C6	FP-TAJT-MFG	CMP-04424-000626-1	1
100n		C7, C8, C9	CAPC2013X145X48NL20T23	CMP-2007-03172-1	3
100u	ALU POLY SMD 7343 100UF 20% 12.5	C11, C12, C13, C15, C16, C17, C18, C19, C20	FP-A700X107M12RATE012-MFG	CMP-03016-000017-1	9
SS14FL	DIODE SCHOTTKY 40V 1A SOD123F	D1	FP-425AD-MFG	CMP-07162-000013-1	1
TVS1401DRBR	IC UNIDIR PRECISION SURGE DIODE	D2, D3, D4, D5	FP-DRB0008A-MFG	CMP-04985-000021-1	4
178.6164.0001	FUSE HOLDER BLADE 80V PCB	F1, F2, F4, F5, F6	FP-178_6164_0001-MFG	CMP-08604-000013-1	5
0031.8231	FUSE BLOK CARTRIDGE 600V 16A PCB	F3	FP-0031_8231-MFG	CMP-26292-000005-1	1
3557-15	Hardware	H1	355715	3557-15	1
PPTC021LFBN-RC	Connector	J1, J2, J3, J4, J6, J8	RHDR2W80P0X254_1X2_558X254X850P	PPTC021LFBN-RC	6
XT90PB-F	Connector	J5, J7, J11	XT90PBF	XT90PB-F	3
5-146128-1	CONN HEADER SMD 3POS 2.54MM	J12	FP-5-146128-1-MFG	CMP-03369-000030-1	1
33u		L1	WE-LQS_6045	CMP-1354-00075-2	1
33u	SMD Power Inductors 33uH ±20% 1.1A 0.286Ω	L2	FP-NR6028-MFG	CMP-14484-001265-1	1
74650194R	74650194R Bush, THR, internal blind-hole thread, 10 mm W x 7 mm H, M4, 9 Pins	MP1, MP2, MP3, MP4, MP5, MP6, MP7, MP8, MP9, MP10, MP11, MP12	74650194	CMP-03913-78872230-	#
Rfbt	RES SMD 10K OHM 1% 1/16W 0402	R1	FP-CRCW0402-e3-IPC_B	CMP-2002-08135-2	1
1k		R2, R5, R6	RESC1608X55X30LL15T15	CMP-2000-00180-1	3
Rfbb	RES Thick Film, 3.24kΩ, 1%, 0.063W, 100ppm/°C, 0402	R3	FP-CRCW0402-e3-MFG	CMP-2002-08579-2	1
3.6	3.6Ω ±5% 0.4W 0805 Anti-Surge Chip Resistor AEC-Q200	R4	FP-ESR10-IPC_A	CMP-08839-028824-1	1
ACS711KEXLT-31AB-T	Hall Effect Linear Current Sensor with Overcurrent Fault Output for <100 V Isolation Applicatio	U1, U3, U4	ALEG-EX-12_V	CMP-1557-00002-1	3
TPS5410DR	Buck Step Down Regulator with 5.5 to 36 V Input and 1.23 to 31 V Output, -40 to 125 degC, 8-Pi	U2	D0008A_L	CMP-0323-00174-3	1

BOM_LDM_POWER_PCB

Figure 6: Bill of materials for the LDM power delivery PCB

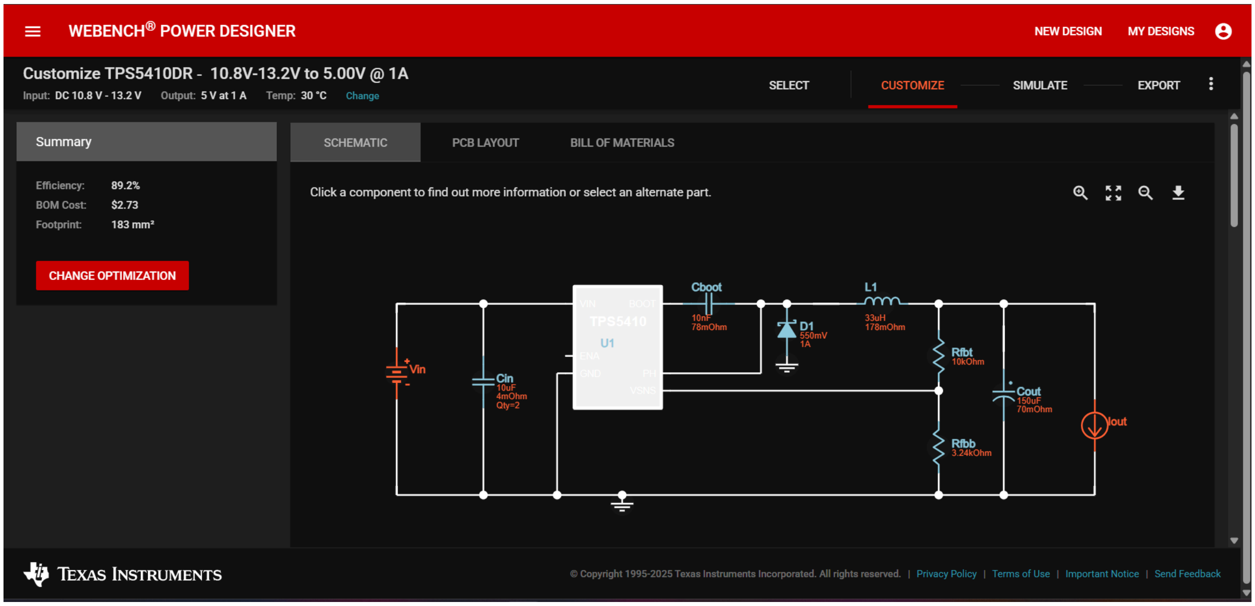


Figure 7: Buck converter design using Texas Instruments' Webbench design tool

Name	Value	Category	Description
Phase Marg	61.42 °	System Information	Bode Plot Phase Margin
Cross Freq	17.46 kHz	System Information	Bode plot crossover frequency
Vout	5 V	System Information	Operational Output Voltage
IC Tolerance	18.32 mV	IC	IC Feedback Tolerance
Cin IRMS	453.44 mA	Capacitor	Input capacitor RMS ripple current
Cin Pd	411.22 µW	Capacitor	Input capacitor power dissipation
Cout IRMS	57.5 mA	Capacitor	Output capacitor RMS ripple current
Cout Pd	231.47 µW	Capacitor	Output capacitor power dissipation
Duty Cycle	0.4008	System Information	Duty cycle
Efficiency	0.892	System Information	Steady state efficiency
Frequency	500 kHz	System Information	Switching frequency
IC Tj	40.96 °C	IC	IC junction temperature
ICThetaJA	75 °C/W	IC	IC junction-to-ambient thermal resistance
L Ipp	199.2 mA	Inductor	Peak-to-peak inductor ripple current
L Pd	195.8 mW	Inductor	Inductor power dissipation
IC Pd	146.09 mW	IC	IC power dissipation
Diode Pd	260.41 mW	Diode	Diode power dissipation
D1 Tj	66.46 °C	Diode	D1 junction temperature
Pout	5 W	System Information	Total output power
Iin Avg	424.47 mA	IC	Average input current
IC Ipk	0	IC	Peak switch current in IC
Mode	CCM	System Information	Conduction Mode
Vout p-p	13.18 mV	System Information	Peak-to-peak output ripple voltage
M Vds Act	76.12 mV	Mosfet	Voltage drop across the MosFET
M Irms	633.11 mA	Mosfet	MOSFET RMS ripple current
Total Pd	602.94 mW	Power	Total Power Dissipation
FootPrint	183 mm²	System Information	Total Foot Print Area of BOM components
Vin	13.2 V	System Information	Vin operating point
Iout	0.041666667	System Information	Iout operating point
Cin Pd	411.22 µW	Power	Input capacitor power dissipation
Cout Pd	231.47 µW	Power	Output capacitor power dissipation
L Pd	195.8 mW	Power	Inductor power dissipation
IC Pd	146.09 mW	Power	IC power dissipation
Diode Pd	260.41 mW	Power	Diode power dissipation
Vout Actual	4.99 V	System Information	Vout Actual calculated based on selected voltage divider resistors
Vout Toleranc	0.0305	System Information	Vout Tolerance based on IC Tolerance (no load) and voltage divider resistors if applicable

Figure 8: Design parameters from the buck converter design using Texas Instruments' Webbench design tool

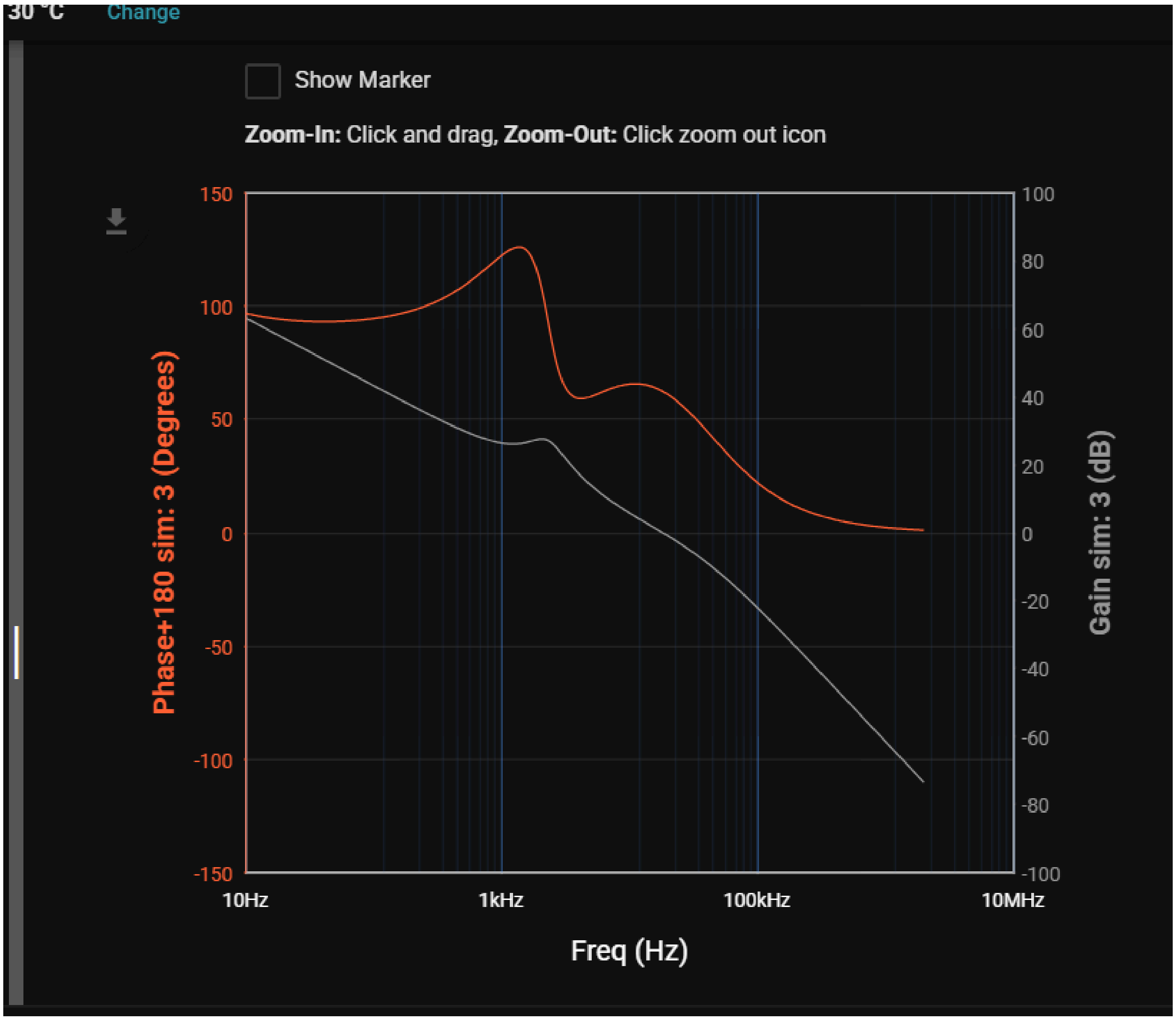


Figure 9: Bode plot from the buck converter design using Texas Instruments' Webbench design tool

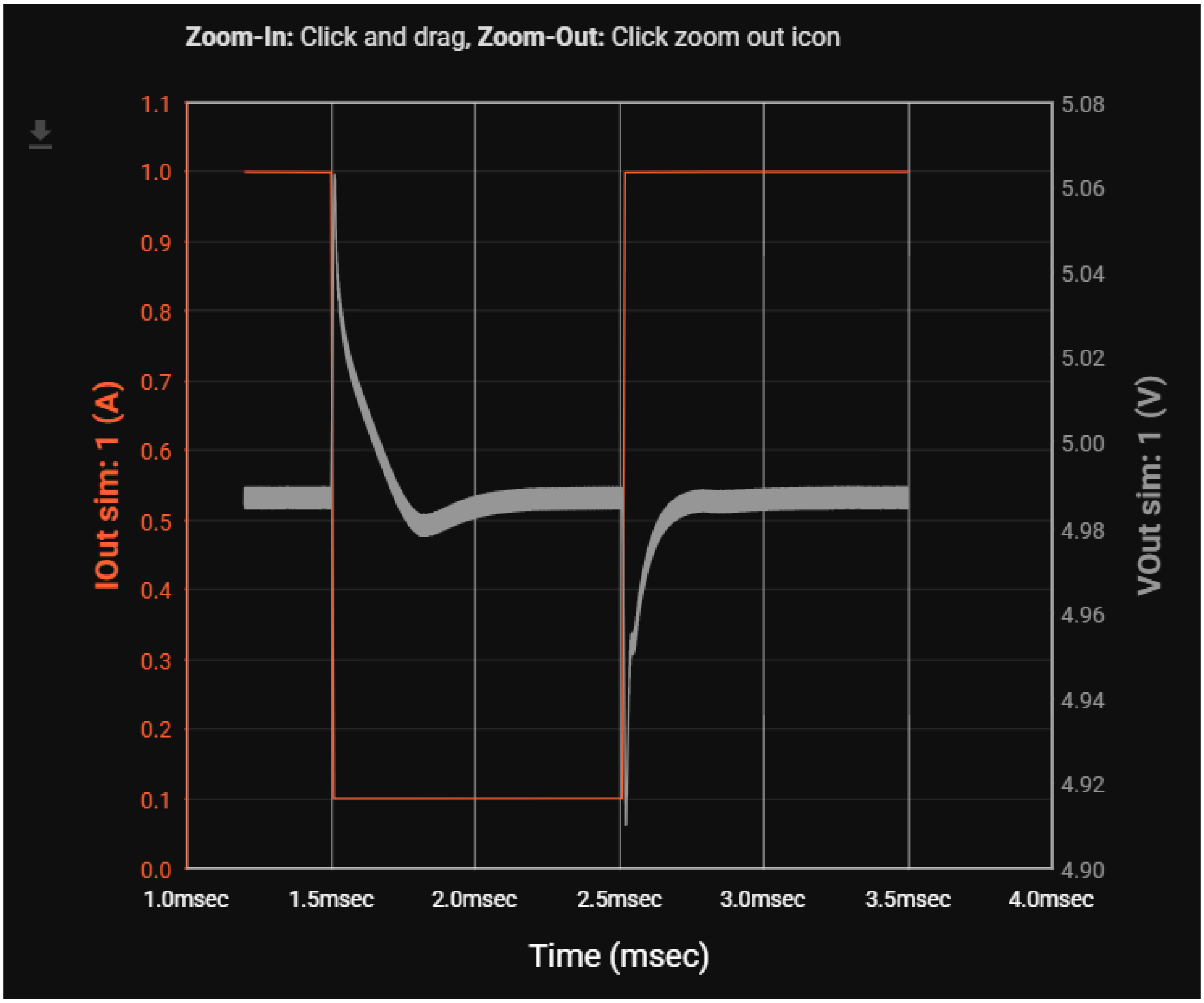


Figure 10: Load transient from the buck converter design using Texas Instruments' Webbench design tool

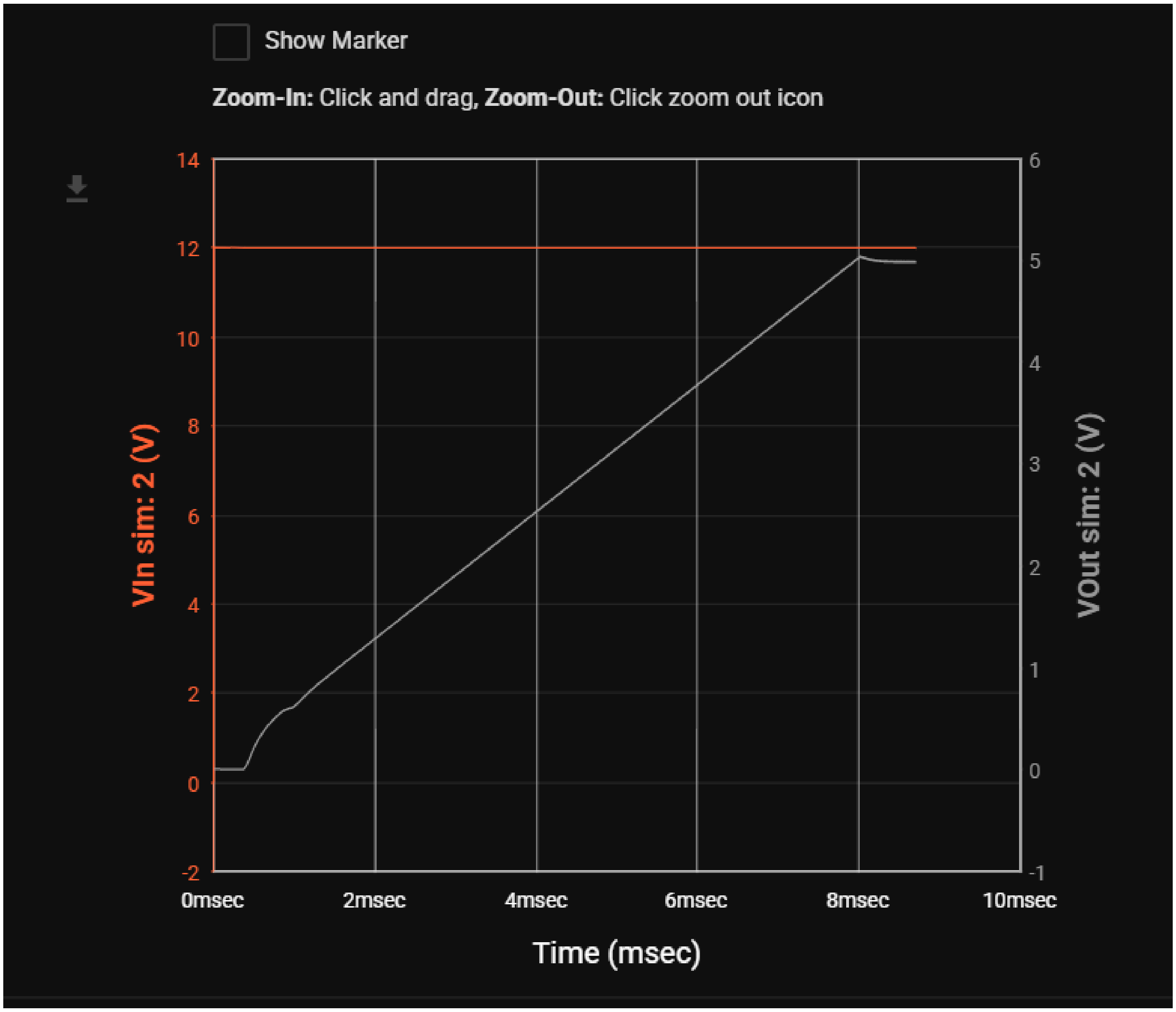
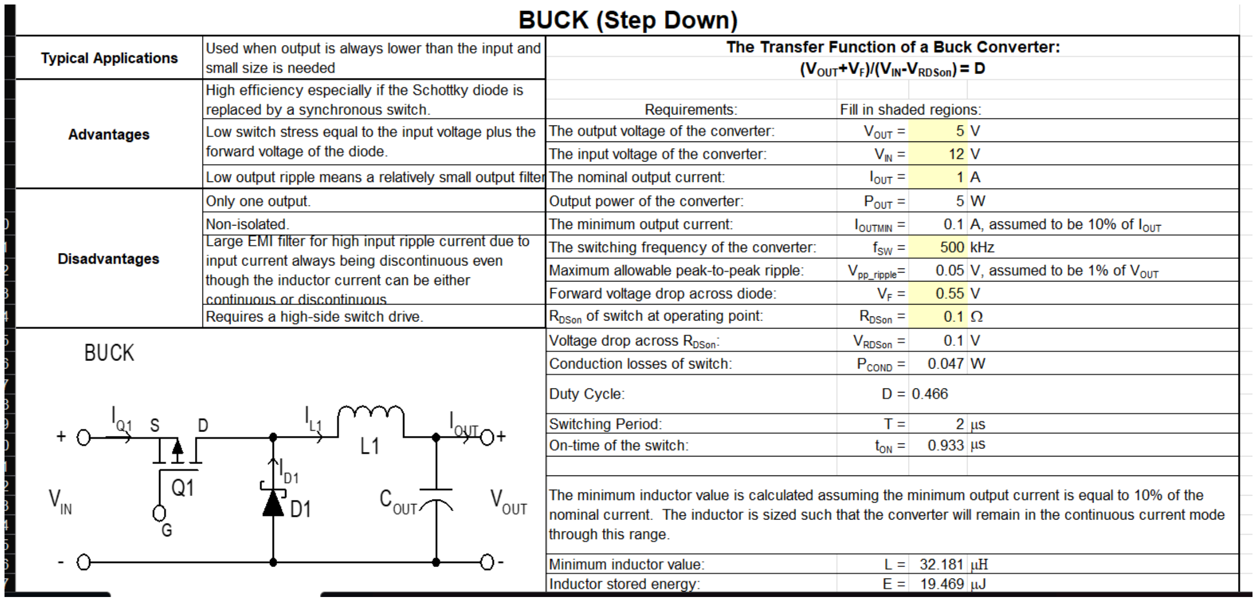


Figure 11: startup transient from the buck converter design using Texas Instruments' Webbench design tool



BUCK (Step Down)

Typical Applications	Used when output is always lower than the input and small size is needed
Advantages	High efficiency especially if the Schottky diode is replaced by a synchronous switch.
	Low switch stress equal to the input voltage plus the forward voltage of the diode.
	Low output ripple means a relatively small output filter
Disadvantages	Only one output.
	Non-isolated.
	Large EMI filter for high input ripple current due to input current always being discontinuous even though the inductor current can be either continuous or discontinuous
	Requires a high-side switch drive.

The Transfer Function of a Buck Converter:

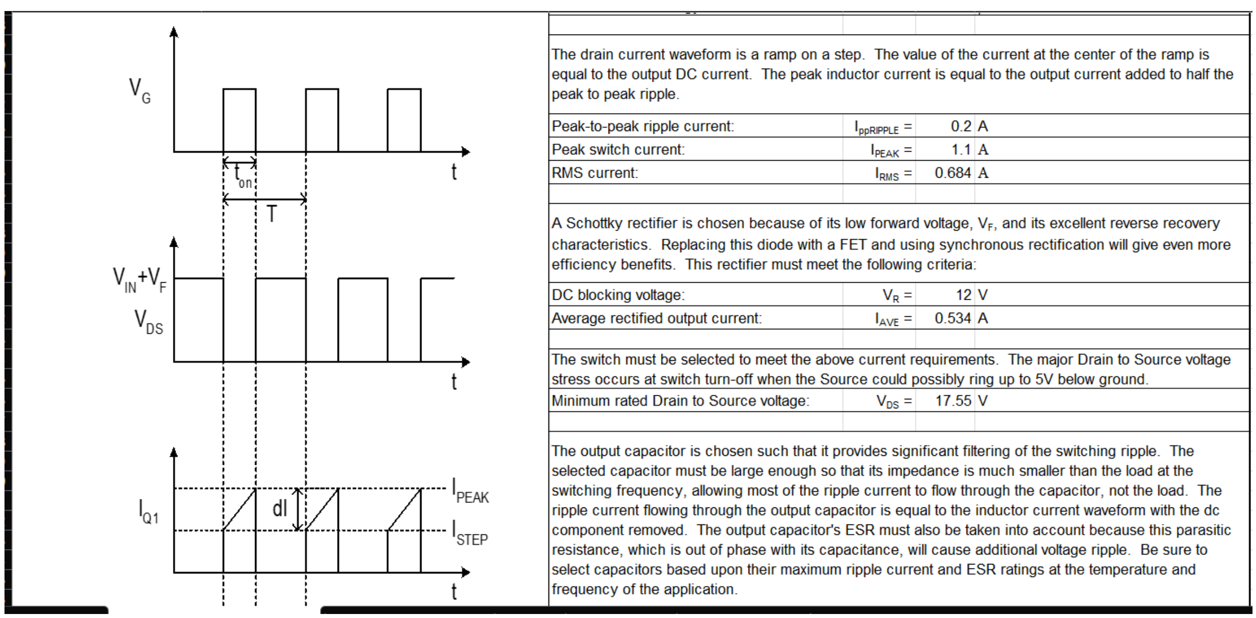
$(V_{OUT}+V_F)/(V_{IN}-V_{RDSon}) = D$

Requirements:	Fill in shaded regions:		
The output voltage of the converter:	V_{OUT} =	5	V
The input voltage of the converter:	V_{IN} =	12	V
The nominal output current:	I_{OUT} =	1	A
Output power of the converter:	P_{OUT} =	5	W
The minimum output current:	I_{OUTMIN} =	0.1	A, assumed to be 10% of I_{OUT}
The switching frequency of the converter:	f_{SW} =	500	kHz
Maximum allowable peak-to-peak ripple:	V_{pp_ripple}=	0.05	V, assumed to be 1% of V_{OUT}
Forward voltage drop across diode:	V_F =	0.55	V
R_{DSon} of switch at operating point:	R_{DSon} =	0.1	Ω
Voltage drop across R_{DSon}:	V_{RDSon} =	0.1	V
Conduction losses of switch:	P_{COND} =	0.047	W
Duty Cycle:	D =	0.466	
Switching Period:	T =	2	µs
On-time of the switch:	t_{ON} =	0.933	µs

The minimum inductor value is calculated assuming the minimum output current is equal to 10% of the nominal current. The inductor is sized such that the converter will remain in the continuous current mode through this range.

Minimum inductor value:	L =	32.181	µH
Inductor stored energy:	E =	19.469	µJ

Figure 12: Buck converter design using Texas Instruments’ buck converter design tool part 1



The drain current waveform is a ramp on a step. The value of the current at the center of the ramp is equal to the output DC current. The peak inductor current is equal to the output current added to half the peak to peak ripple.

Peak-to-peak ripple current:	$I_{ppRIPPLE}$ =	0.2	A
Peak switch current:	I_{PEAK} =	1.1	A
RMS current:	I_{RMS} =	0.684	A

A Schottky rectifier is chosen because of its low forward voltage, V_F, and its excellent reverse recovery characteristics. Replacing this diode with a FET and using synchronous rectification will give even more efficiency benefits. This rectifier must meet the following criteria:

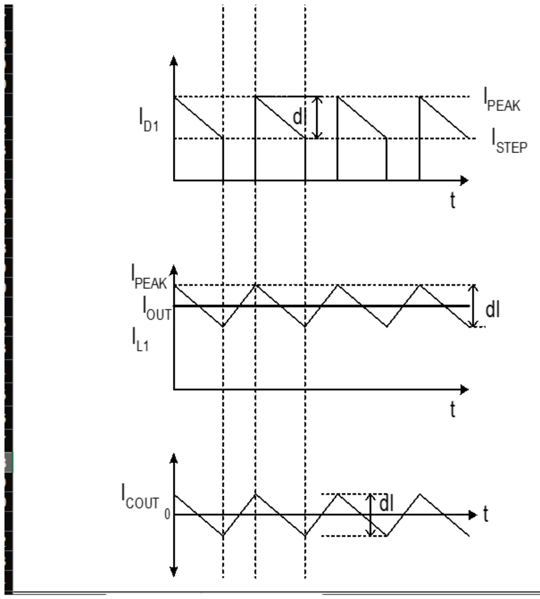
DC blocking voltage:	V_R =	12	V
Average rectified output current:	I_{AVE} =	0.534	A

The switch must be selected to meet the above current requirements. The major Drain to Source voltage stress occurs at switch turn-off when the Source could possibly ring up to 5V below ground.

Minimum rated Drain to Source voltage:	V_{DS} =	17.55	V

The output capacitor is chosen such that it provides significant filtering of the switching ripple. The selected capacitor must be large enough so that its impedance is much smaller than the load at the switching frequency, allowing most of the ripple current to flow through the capacitor, not the load. The ripple current flowing through the output capacitor is equal to the inductor current waveform with the dc component removed. The output capacitor's ESR must also be taken into account because this parasitic resistance, which is out of phase with its capacitance, will cause additional voltage ripple. Be sure to select capacitors based upon their maximum ripple current and ESR ratings at the temperature and frequency of the application.

Figure 13: Buck converter design using Texas Instruments’ buck converter design tool part 2



Output capacitor RMS ripple current:	I_{RMScap} =	0.058 A
Minimum output capacitance:	C_{OUT} =	1.00 µF
Chances are, a bank of capacitors will be required to handle the output ripple current. This capacitance will have an ESR associated with it:		
Total capacitance of output bank used:	$C_{OUTbank}$ =	150 µF
Maximum ESR required:	ESR_{MAX} =	0.25 Ω
Actual ESR of output capacitor bank used:	ESR =	0.088 Ω
Peak-to-peak voltage ripple due to output capacitance:	V_{PPcap} =	0.000 V
Peak-to-peak voltage ripple due to output ESR:	V_{PPESR} =	0.018 V
Resultant total peak-to-peak output voltage ripple:	$V_{PPtotal}$ =	0.018 V
The same logic is applied when selecting the input capacitor. This capacitor, or bank of capacitors, will experience very high ripple current; the same current that is at the switch drain. An acceptable level of input voltage ripple which would still maintain regulation is assumed to be 5%.		
Input capacitor RMS ripple current:	I_{RMS} =	0.684 A
Acceptable input voltage ripple:	$V_{rippleIN}$ =	0.600 V, assumed to be 5% of V_{IN}
Minimum input capacitance:	C_{IN} =	0.4583 µF
Total capacitance of input bank used:	C_{INbank} =	10 µF
Maximum ESR required:	ESR_{MAX} =	0.5449 Ω
Actual ESR of input capacitor bank used:	ESR =	0.1 Ω
Peak-to-peak voltage ripple due to input capacitance:	V_{PPcap} =	0.028 V
Peak-to-peak voltage ripple due to input ESR:	V_{PPESR} =	0.110 V
Resultant total peak-to-peak input voltage ripple:	$V_{PPtotal}$ =	0.113 V

Figure 14: Buck converter design using Texas Instruments' buck converter design tool part 3

A	B	C	D	E	F	G	H	I	J	K	L
TPS5410	Nominal (mV):	Vin Ripple (max) (mV):	Vin Ripple (max)(%):	Vin Ripple (max)(dB):							
	12000	166	0.013833333	18.59073158							
2nd order parallel damped LC filter:Input											
	f_crossover/f_0 (kHz):	C_d (uF):	R_d (ohm)	C (uF):	L (uH):	Z_0 (ohm)	Z_Cd (ohm)	Z_C (ohm)	Z_L(ohm)	Z_out(ohm)	zeta_optimal:
theoretical	18	10	3.536776513	2.5	31.27197026	50	0.884194128	3.536777	3.536776513	1.26	0.6123
actual	17.52238254	10	3.6	2.5	33	N.A.	0.908295106	3.63318	3.442930612	1.27	
Note: Not enough info to calculate actual characteristic impedance Z_0 of the T.L.											
	Vin Ripple (max) (V):	I_out(max) (A):	f_switching (kHz):	C_bulk (uF)	I_in_ripple(max) (A):	Vin(max) (V)	Vout (V):	L_out (uH)	I_L_RMS (A):	I_L_pk (A):	
	0.165788063	1.2	500	10	0.6	12	5	33	1.200048241	1.3104798	
	f_LC (corner frequency) (kHz)	C_out(uF)	ESR(Max) (ohm):	V_pp(max) (V):	I_Cout_ripple(RMS) (uA)						
	2.728921505	103.0318641	0.088156719	0.019479073	25.25250003						

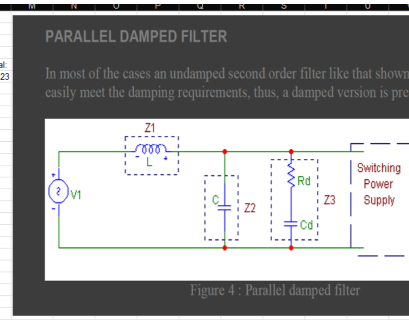


Figure 15: EMI input filter of buck converter design using white paper recommendations from Texas Instruments'

The PCB stackup is a typical 4-layer stackup, with standard overall thickness of 1.57mm.The material choice per layer was made based on availability within the Altium library. The layer thickness choice of 1oz per layer was recommended by the Electrical Systems subteam leader. The design choices of trace width for current capacity, via quantity and spacing on stitched via polygons, characteristic impedance,EMI filter design, and various other design choices were made by: referencing the material in the references, from design recommendations from device datasheets , and from Texas Instruments' Webbench design and Buck Converter Design tools.Design choices on via types, via diameter, via hole size, as well as trace widths, were all made by referencing the JLC PCB DFM capabilities w since this is the usual vendor selected by the uOttawa Mars Rover team. More specific details on the design choices and calculations are included in the associated excel documents of the project.

Design challenges:

- Integrating 12 awg wire interconnects with the PCB traces into and out of board for the motor controllers and the motors themselves.
- Optimizing PCB spacing and component placement on the board.
- Current carrying capacity of respective motor supply lines.

Design solutions:

- Strategic placement of XT90 connectors, screw terminals,and bus bar copper pours on the PCB to pop in and out of the PCB where needed.
- Careful planning and iterative testing in the component placement stage before routing.
- Using IPC 2221 formulas and parameters to calculate the minimum copper pour width ,minimum via spacing of the stitching vias, via type, via hole size, and via pad diameter needed to carry the required current through the copper pour and ensure current flow between both top and bottom layers of the stitched copper pours.

Conclusion:

This project presented an exciting new challenge for me. It was my first real opportunity to implement a PCB design entirely on my own, as well as my first opportunity designing a power delivery system.This design proposed an unconventional challenge of interfacing 12 awg gauge wire connections into and out of the PCB, as well as integrating the various motor controllers and analog current sensors with the microcontroller. I received some initial guidelines from the Electrical Systems and Life Detection subteam leader; after which, I was granted full autonomy on the design and implementation of the PCB. I am grateful to both subteam leaders for entrusting me with the opportunity to produce a design which would meet the needs of the Life Detection Module of the uOttawa Mars Rover.I enjoyed learning how to use the Altium Designer software, as well as other PCB-specific calculations and tools, along with the theory I have been studying in my EE undergrad, in order to deliver a fully-functioning power delivery system for the uOttawa Mars Rover. Overall this project has been a fun challenge with many lessons learned along the way, and I am grateful to have had the opportunity to pursue this project while in my final year of my EE undergrad. As I graduated this year, I am leaving this design in the capable hands of the Electrical Systems and Life Detection subteam leaders for purchasing, testing, and potential iterations as needed.I wish them the best of luck in their future endeavours with the uOttawa Mars Rover team!

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