EE 394V – Demo Board for DC-DC converters

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Introduction

In this project, we designed and analyzed a canonical cell implementation of buck, boost and buck-boost converters on a single PCB. All converter implementations use the same power stage components but with different configurations. The primary design objective is to demonstrate the effects of changing duty cycle and frequency, as well as capacitance, inductance and load in different parts of the circuit for all converter modes. The converter mode is selected using a 4-pole 3-throw (4P3T) switch.

This report first demonstrates the implementation of all required and two elective features. A list of possible improvements then follows. Finally, the rationales for every component selection are listed in Appendix A.

Required Features

1. *Configuration change*

The input and output voltages for different 4P3T settings and their corresponding converter modes are shown in Table 1. This validates that each mode operates as it should: the buck mode reduces voltage, the boost mode increases voltage, and the buck-boost mode can do both.

	V_{in} (V)	V_{out} (V)
Buck	5	2.47 (D=0.5)
Boost	5	9.47 (D=0.5)
Buck- Boost	5	3.125 (D=0.4) 6.76 (D=0.6)

Table 1: Demonstrating buck, boost, and buck-boost converter operation at f=15 kHz

2. *Sensing inductor current and capacitor voltage (with ripples)*

Inductor currents are sensed using a current probe amplifier. Figures 1, 2 and 3 show the oscilloscope waveforms of the inductor current in buck, boost and buck-boost modes respectively.

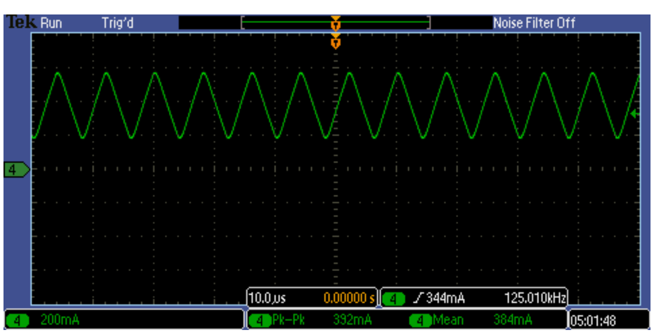

Figure 1: Inductor current for buck mode (V_{in}=10 V, f=125 kHz, D=0.5, R=10 Ohm, L=47 µH)

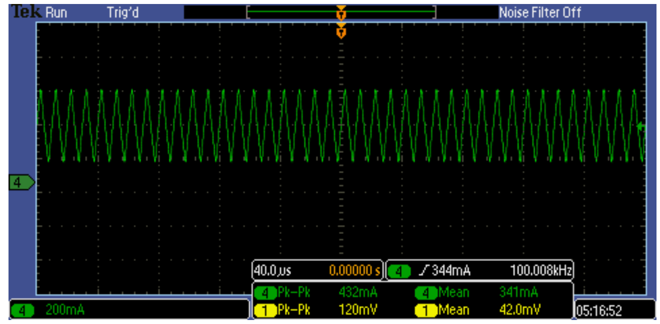

Figure 2: Inductor current for boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=40 Ohm, L=47 µH)

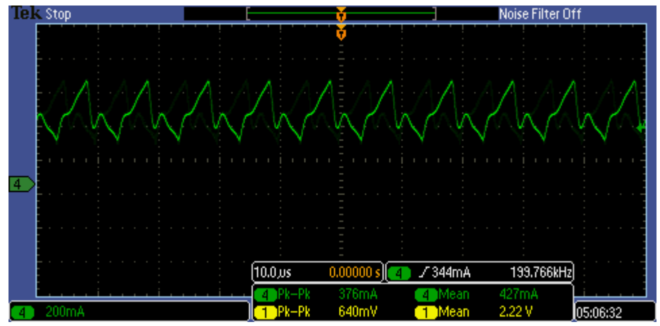

Figure 3: Inductor current for buck-boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=10 Ohm, L=47 µH)

Output capacitor voltages are sensed using oscilloscope probes grounded using spring clips. Figures 4, 5 and 6 show the oscilloscope waveforms of the output capacitor voltage in buck, boost and buck-boost modes respectively.

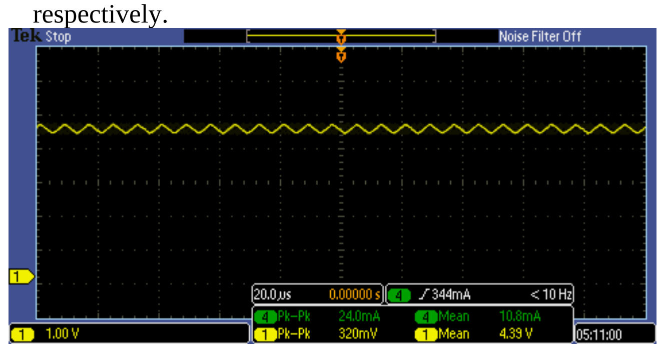

Figure 4: Output capacitor voltage for buck mode (V_{in}=10 V, f=125 kHz, D=0.5, R=10 Ohm, C=47 µF)

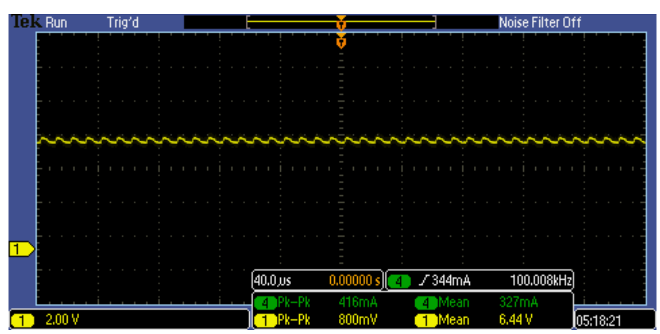

Figure 5: Output capacitor voltage for boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=40 Ohm, C=47 µF)

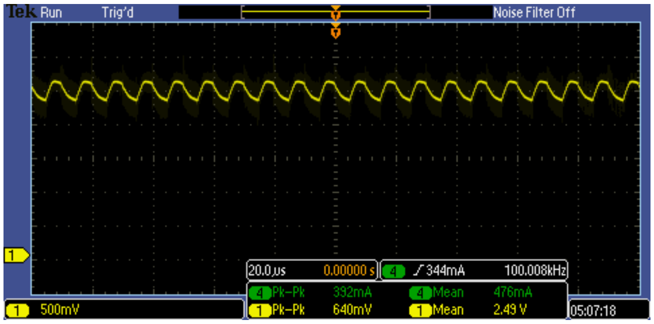

Figure 6: Output capacitor voltage for buck-boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=10 Ohm, C=47 µF)

3. *Gate Source voltage and switch-node voltage*

Figure 7 shows the waveform for the gate-source voltage at switch Q2 measured in buck mode, in which Q2 acts as the low side switch with its source grounded. An identical waveform was observed for boost and buck-boost modes.

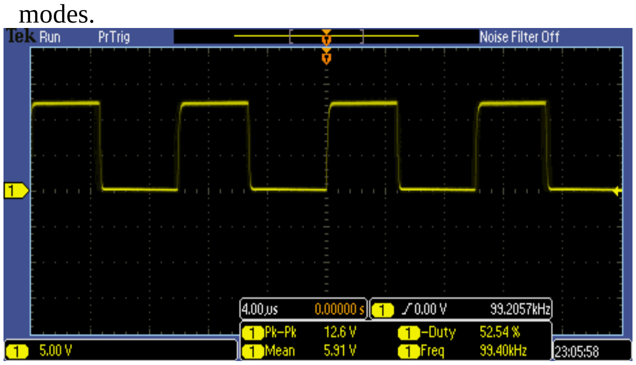

Figure 7: V_{GS} for switch Q2 (D=0.5, f=100 kHz)

Figure 8 shows the switch node voltage in buck mode. The shape of the waveform remains same across all modes.

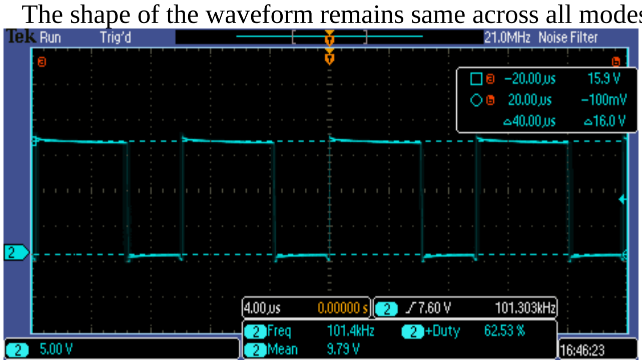

Figure 8: Switch node voltage in buck mode (V_{in}=16 V, D=0.62, f=100 kHz)

4. *Effects of varying inductance and capacitance*

A. *Varying power stage inductor*

In the power stage, two 47µH inductors are configured in parallel, with one of them having a mechanical switch in its branch. When the switch is OFF, only the other inductor carries current through it, so the net inductance is 47 µH. When the switch is ON, both inductors are connected in parallel, resulting in a net inductance of 23.5 µH.

Figures 1, 2, and 3 (shown before) depict inductor current waveforms for the 47 µH case in buck, boost and buck-boost modes respectively. Figures 9, 10, and 11 show inductor current waveforms for the 23.5 µH case in buck, boost and buck-boost mode respectively. It can be observed that decreasing inductance leads to an increased inductor current ripple, causing the circuit to approach DCM.

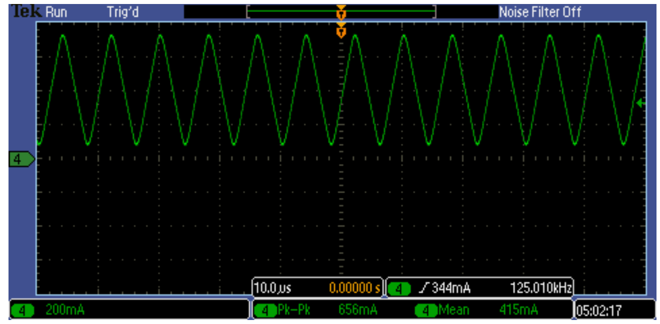

Figure 9: Inductor current for buck mode (V_{in}=10 V, f=125 kHz, D=0.5, R=10 Ohm, L=23.5 µH)

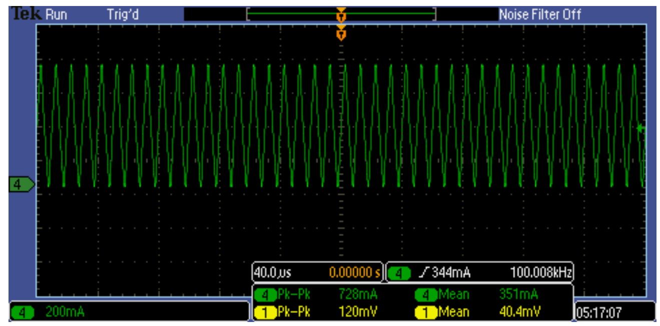

Figure 10: Inductor current for boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=40 Ohm, L=23.5 µH)

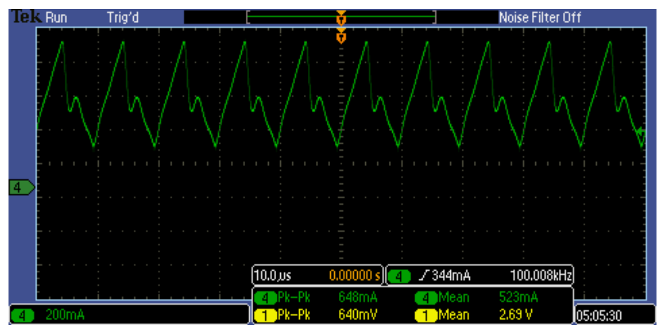

Figure 11: Inductor current for buck-boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=10 Ohm, L=23.5 µH)

B. *Varying output capacitance*

Two 47 µF capacitors are configured in parallel at the output, with one of them having a mechanical switch in its branch. When the switch is OFF, only the other capacitor carries current through it, so the net capacitance is 47 µF. When the switch is ON, both capacitors are connected in parallel resulting in a net capacitance of 94 µF.

Figures 4, 5, and 6 (shown before) depict output capacitor voltage waveforms for the 47 µF case in buck, boost and buck-boost modes respectively. Figures 12, 13, and 14 show output capacitor voltage waveforms for the 94 µF case in buck, boost and buck-boost mode respectively. It can be observed that increasing capacitance leads to a decreased output voltage ripple.

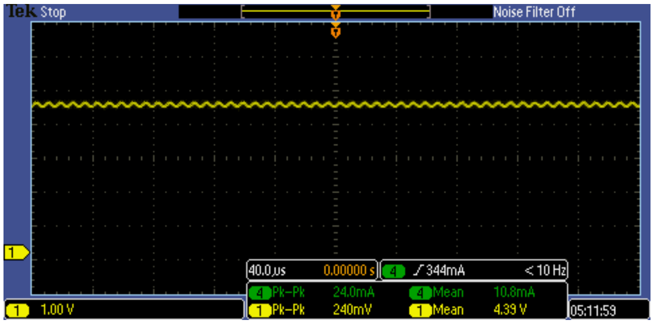

Figure 12: Output capacitor voltage for buck mode (V_{in}=10 V, f=125 kHz, D=0.5, R=10 Ohm, C=94 µF)

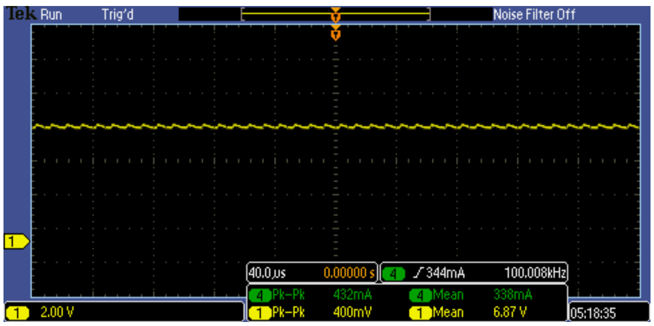

Figure 13: Output capacitor voltage for boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=40 Ohm, C=94 µF)

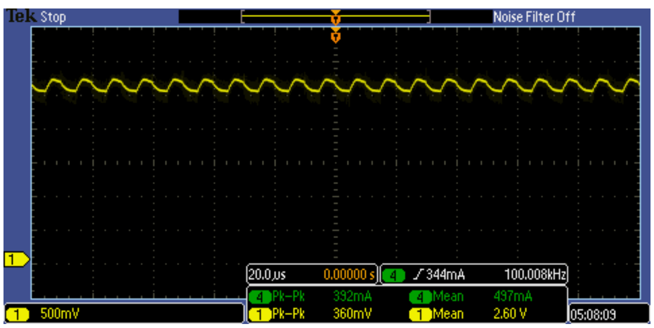

Figure 14: Output capacitor voltage for buck-boost mode (V_{in}=4 V, f=100 kHz, D=0.5, R=10 Ohm, C=94 µF)

5. *Diode operation and synchronous rectification*

It is possible to toggle between diode operation and synchronous rectification modes in the microcontroller code by setting the variable *Synchro* (0 for diode operation, 1 for synchronous rectification). The diode operation employs the body diode of the appropriate transistor in each mode.

Table 2 lists the efficiencies for diode operation and synchronous rectification operation for the buck mode. It is evident that diode operation sees lower efficiencies for each mode, because of the 0.8 V forward voltage drop of the body diodes.

6. *Effect of loop inductance on gate source and switch node voltages*

A 100 nH inductor is connected in parallel to a mechanical switch in the path between the gate driver and the gate of transistor Q2. When the switch is ON, the 100 nH inductor is short circuited. Whereas when the switch is OFF, the 100 nH inductor is added to the path. Figure 15 shows the gate-source voltage waveform without (top) and with (bottom) the external inductance.

	Buck	Boost	BB
V_{in}	15.97 V	4.98 V	4.98 V
I_{in} (Diode)	0.284 A	0.286 A	0.209 A
V_{out} (Diode)	8.98 V	7.27 V	6.06 V
I_{out} (Diode)	0.418 A	0.166 A	0.144 A
Efficiency (Diode)	82.7%	84.7%	83.8%
I_{in} (Synchronous)	0.262 A	0.314 A	0.218 A
V_{out} (Synchronous)	9.22 V	7.88 V	6.63 V
I_{out} (Synchronous)	0.43 A	0.181 A	0.151 A
Efficiency (Synchronous)	94.75%	91.12%	92.2%

Table 2: Demonstrating buck, boost, and buck-boost converter operation at D=0.5 and f=15 kHz

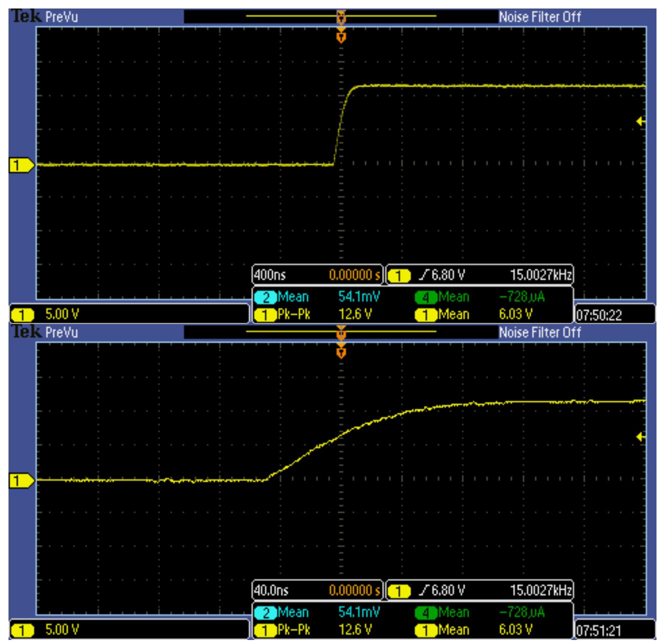

Figure 15: Gate-source voltage - without external inductance (top), and with external 100 nH inductance (bottom) (f=125 kHz, D=0.7)

Theoretically, the extra inductance should cause ringing in the bottom waveform of Figure 15, as it was calculated to give quality factor of more than 0.5 which produces underdamped waveform – but this effect is not conspicuous. Even after reducing the gate driver resistance from 10 Ohm to 2 Ohm which results in even more quality factor, no visible change was observed.

Figure 16 shows the zoomed switch node voltage without (top) and with (bottom) the external inductance. In the bottom waveform, some ringing can be observed– caused due to the extra inductance. However, this is not the type of ringing that extra inductance would result in, yet the effect was observed every time switching was done.

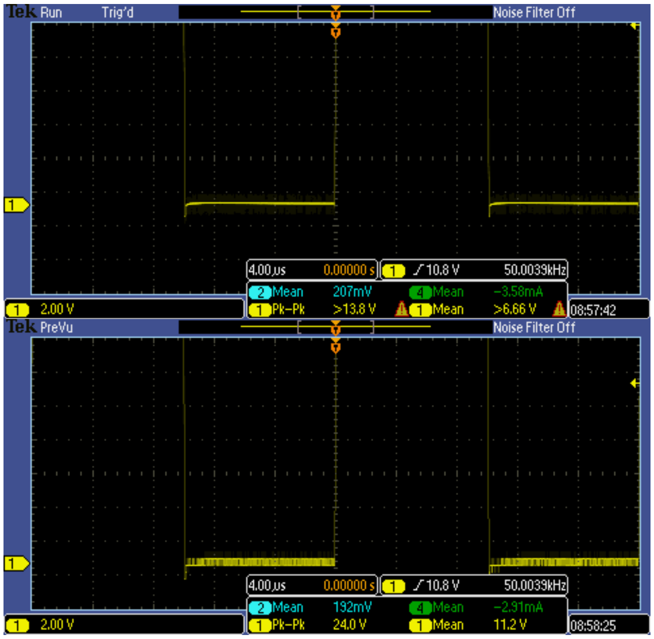

Figure 16: Zoomed switch node voltage - without external inductance (top), and with external 100 nH inductance (bottom) (f=125 kHz, D=0.7)

7. *Switching loss through overlap of switch voltage and current*

The waveforms of the transistor Q2 voltage and current in boost mode are shown in Figure 17. The intervals involving an overlap between non-zero current and non-zero voltage cause switching loss. In this case, turn off losses were more pronounced as the circuit was running at almost ZVS.

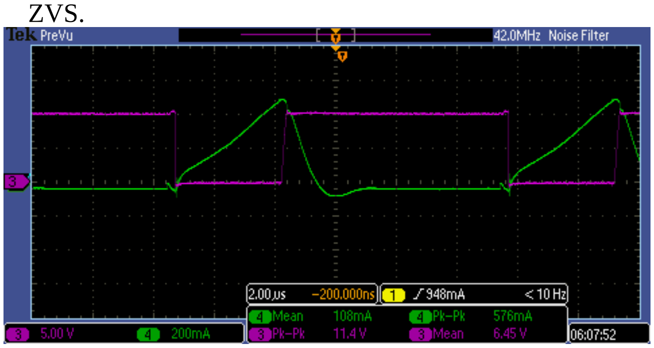

Figure 17: Switch voltage (purple) and current (green) in boost mode (V_{in}=5 V, f=100 kHz, D=0.4, R=40 Ohm)

8. *Diode reverse recovery through diode voltage and current*

The waveforms of the voltage and current of the body diode of transistor Q1 in boost mode are shown in Figure 18. The intervals involving an overlap between negative (reverse recovery) current and positive voltage cause reverse recovery loss.

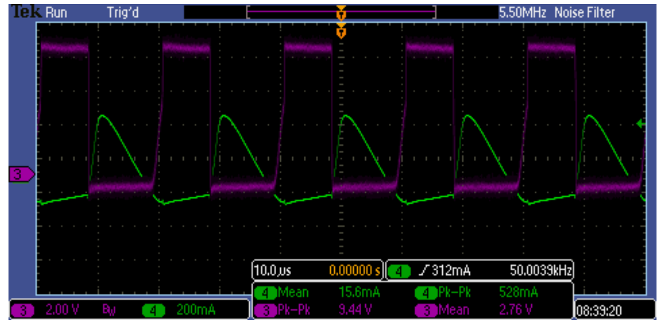

Figure 18: Diode voltage (purple) and current (green) in boost mode (V_{in}=4 V, f=100 kHz, D=0.4, R=40 Ohm)

9. *Effect of various frequencies of operation*

Figures 19, 20 and 21 show the inductor currents for buck, boost and buck-boost modes respectively, at three frequencies each: 30 kHz, 60 kHz and 100 kHz.

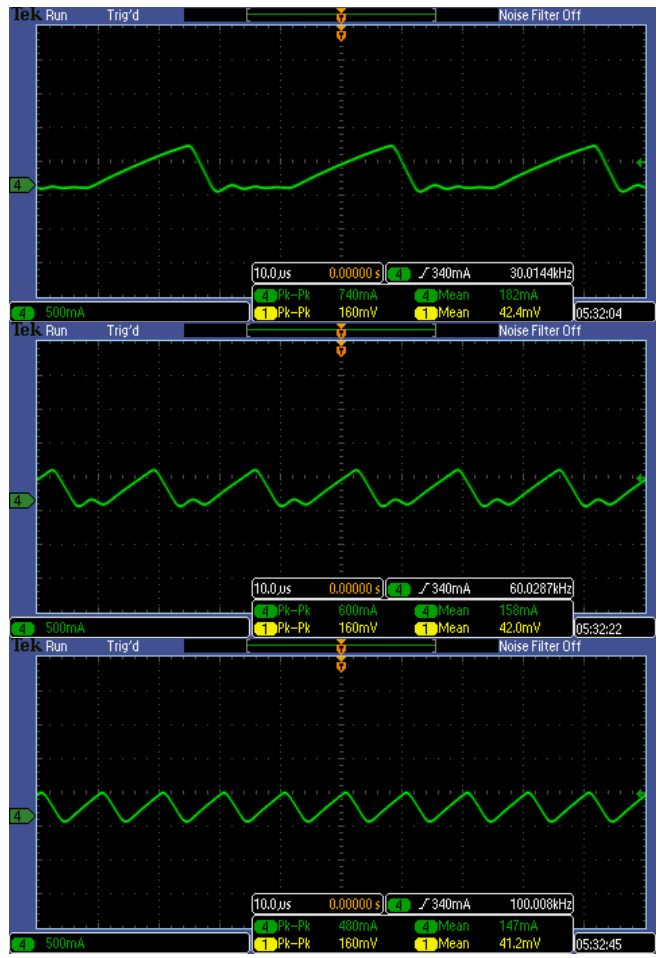

Figure 19: Inductor current in buck mode (V_{in}=10 V, D=0.5, R=40 Ohm, L =47 µH) with f=30 kHz (top), f=60kHz (middle), and f=100kHz (bottom)

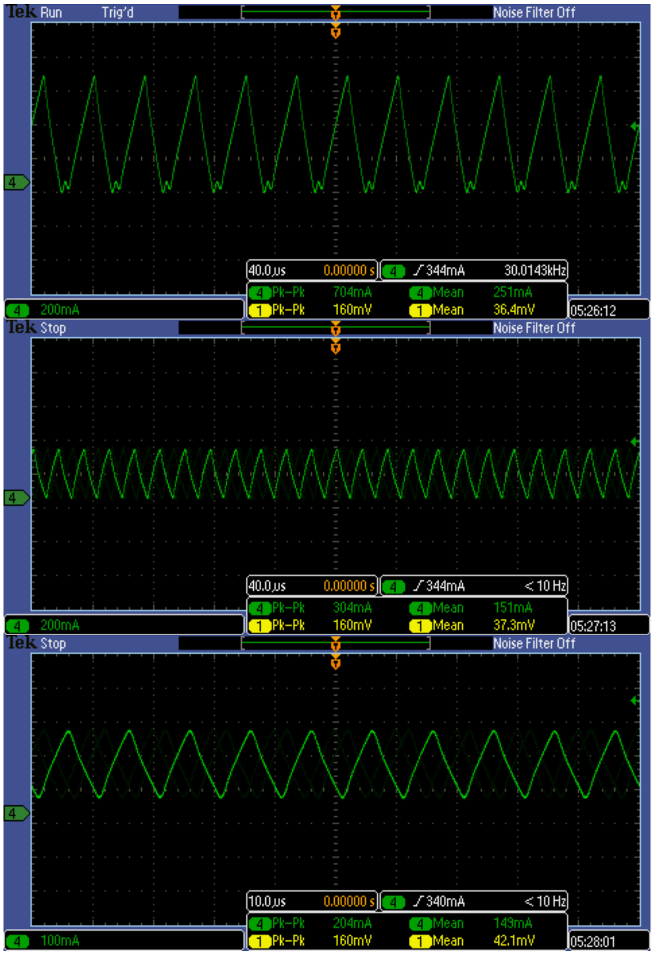

Figure 20: Inductor current in boost mode (V_{in}=4 V, D=0.5, R=40 Ohm, L =47 µH) with f=30 kHz (top), f=60kHz (middle), and f=100kHz (bottom)

It is evident that decreasing frequency causes the inductor current ripple to increase in every mode. Similar increase in ripple was also observed in output capacitor voltages.

10. *Continuous, boundary and discontinuous conduction modes and valley switching*

Figure 1 presented before shows the inductor current in continuous conduction mode in the buck converter. Figure 23 shows discontinuous (top) and boundary conduction modes (bottom) for buck converter.

Figure 2 presented before shows the inductor current in continuous conduction mode in the boost converter. Figure 24 shows discontinuous (top) and boundary conduction modes (bottom) for buck-boost converter.

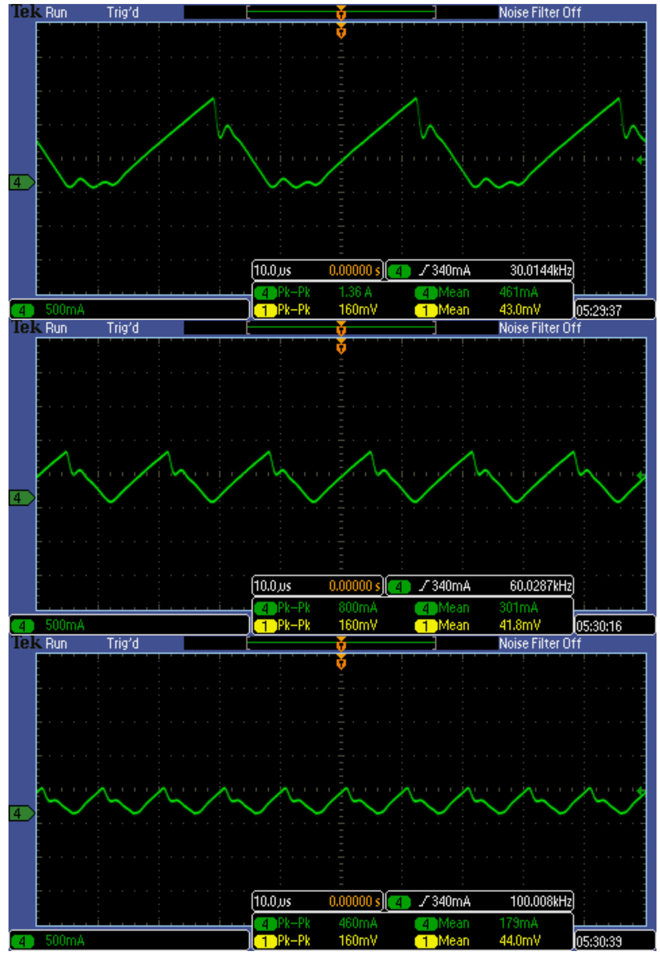

Figure 21: Inductor current in buck-boost mode (V_{in}=4 V, D=0.5, R=40 Ohm, L =47 µH) with f=30 kHz (top), f=60kHz (middle), and f=100kHz (bottom)

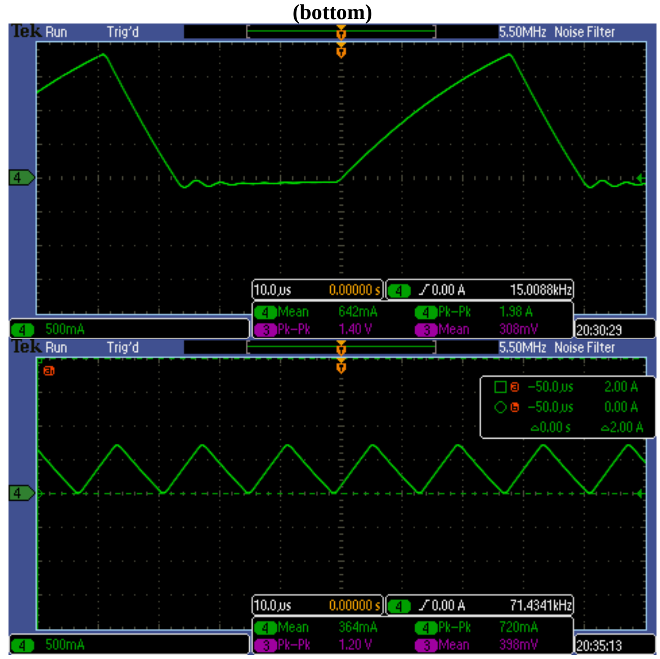

Figure 23: Inductor current in buck converter during discontinuous (top) (V_{in}=10 V, f=30 kHz, D=0.5, R=40 Ohm, L=47 µH) and boundary conduction mode (bottom) (V_{in}=10 V, f=100 kHz, D=0.5, R=10 Ohm, L=47 µH)

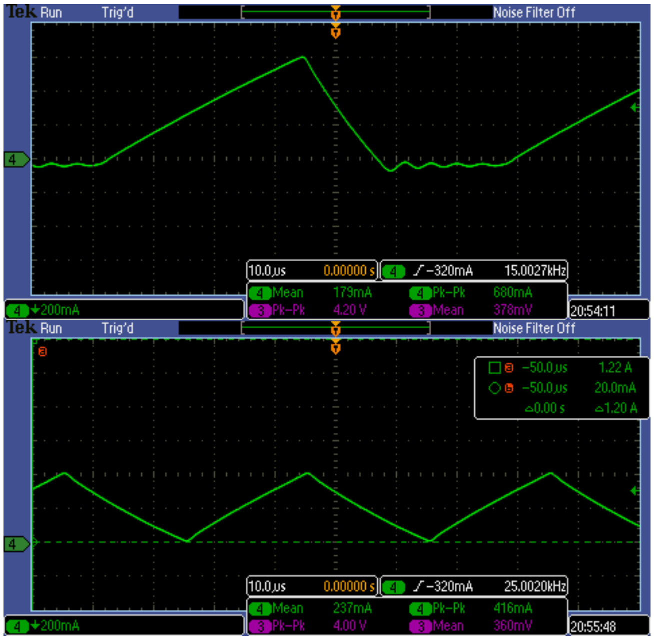

Figure 24: Inductor current in boost converter during discontinuous (top) (V_{in}=4 V, f=30 kHz, D=0.5, R=40 Ohm, L=47 µH) and boundary conduction mode (bottom) (V_{in}=4 V, f=80 kHz, D=0.5, R=40 Ohm, L=47 µH)

Figure 3 presented before shows the inductor current in continuous conduction mode in the buck-boost converter. Figure 25 shows discontinuous (top) and boundary conduction modes (bottom) for buck-boost converter.

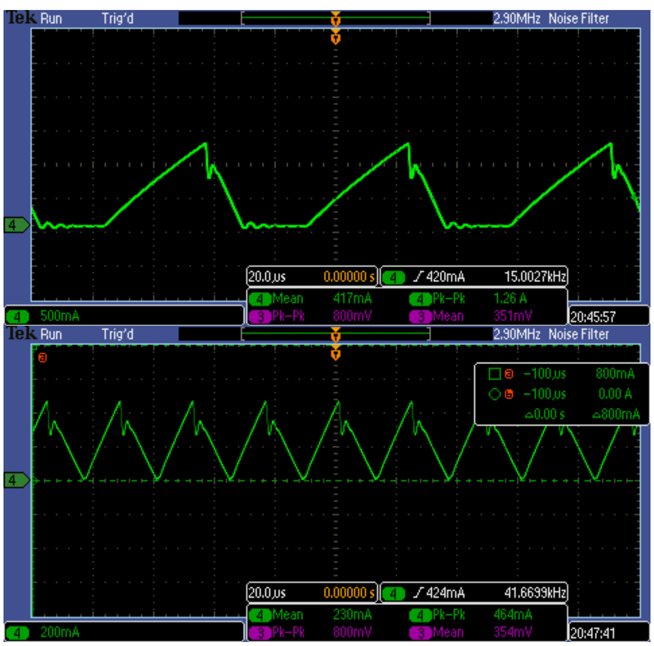

Figure 25: Inductor current in buck-boost converter during discontinuous (top) (V_{in}=4 V, f=30 kHz, D=0.5, R=40 Ohm, L=47 µH) and boundary conduction mode (bottom) (V_{in}=4 V, f=80 kHz, D=0.5, R=10 Ohm, L=47 µH)

Valley switching in boost mode is shown in Figure 26. The switch remains off during the interval indicated by the cursors, which is when the inductor current resonates with the output capacitance (C_{OSS}) of the switch. The switch turns on when the switch voltage becomes 0, helping achieve ZVS turn-on. This mode was achieved by adjusting the dead band of the switch.

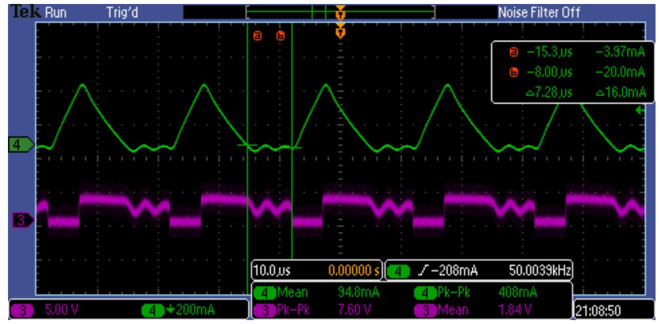

Figure 26: Inductor current (green) and switch voltage (purple) during valley switching in boost mode (V_{in}=4 V, f=60 kHz, D=0.5, R=40 Ohm, L=47 µH, dead band = 200ns)

11. *Output voltage limiting in boost and buck boost modes*

The duty cycle knob is calibrated such that the duty cycle input is not allowed to go below 0.15 or above 0.85. This helps in limiting the output voltage of the boost and buck-boost converters.

12. *Transient response with load step in open and closed loop operation*

The transient responses in open loop and closed loop operation in buck mode are shown in Figures 27 and 28 respectively. The top figure shows the initial waveforms (before the transient) and the bottom figure shows the waveforms after the transient. The transient response could not be captured in a single figure because the output voltage did not change very significantly.

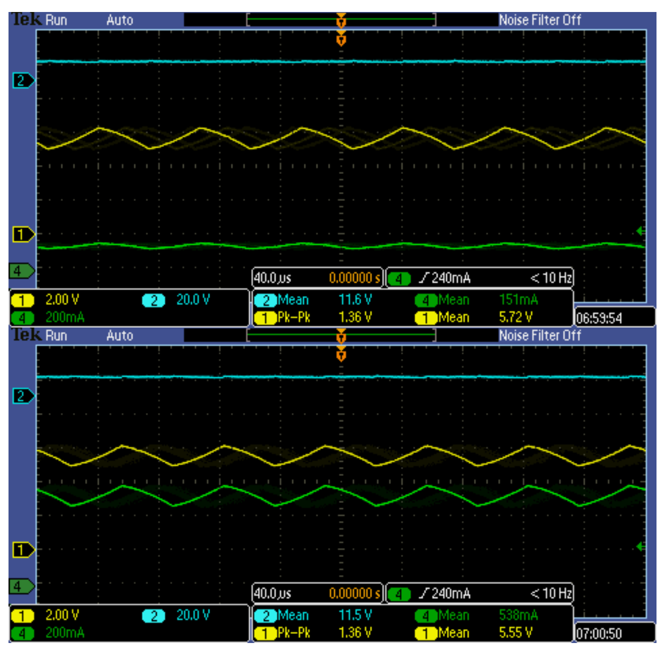

Figure 27: Open loop load transient from 40 Ohm to 10 Ohm - input voltage (blue), output voltage (yellow) and output current (green) for buck mode operation (V_{out} ≈5.6 V, D=0.5, f=30 kHz)

In open loop, the output voltage changes by 0.17 V due to the load step. In closed loop, the output voltage is quite stable – the 0.04 V change can be attributed to be caused by measurement error in the microcontroller.

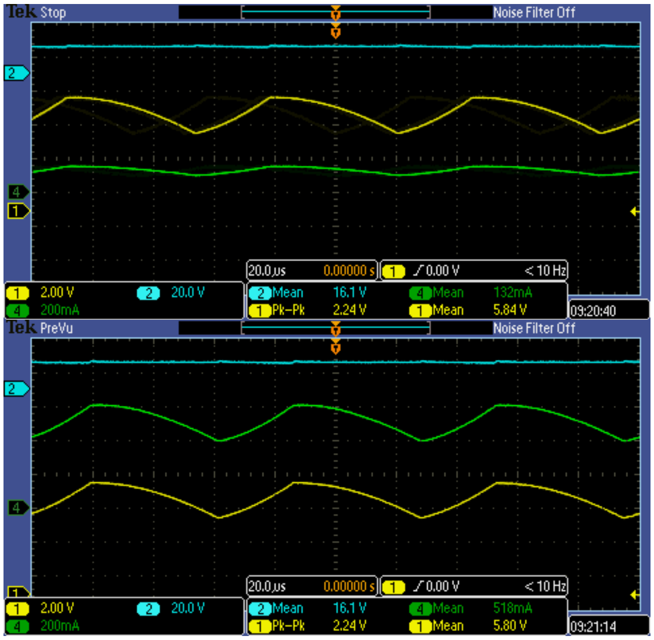

Figure 28: Closed loop load transient from 40 Ohm to 10 Ohm - input voltage (blue), output voltage (yellow) and output current (green) for buck mode operation (V_{out}≈5.8 V, f=30 kHz, R=10 Ohm)

Additionally, the closed loop buck mode operation was studied for an input voltage step change. This is shown in Figure 29. The output voltage was found to remain unchanged.

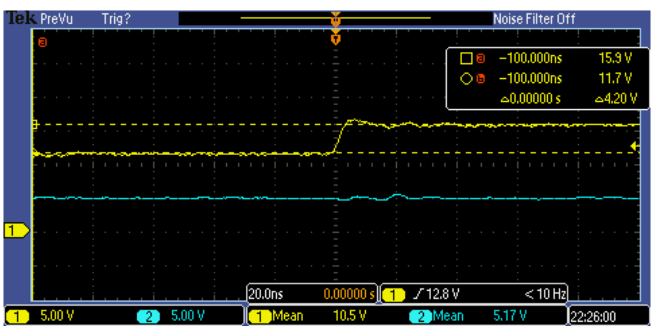

Figure 29: Closed loop transient with V_{in} changing from 11.7 V to 15.9 V - input current (yellow) and output voltage (blue) for buck mode operation (V_{out}≈5.17 V, f=30 kHz, R=10 Ohm)

13. *Future-proof adjustments*

The switches, including 4P3T and trimmer potentiometers used for duty cycle and frequency control are securely mounted on the PCB and are rated for (large number of operations).

14. *High voltage node protection*

The exposed parts of wires were carefully covered using nonconductive tape. Input and output were connected to the PCB using appropriate terminal blocks to add a layer of protection. Also, the switches used to change inductances and capacitances were positioned to prevent any accidental human contact with high voltage nodes during operation. Probing points were placed at a distance from the path for safety.

Elective Features

E1. *Stable closed-loop control over a wide range of operating points*

The transient response in closed loop operation in buck mode is shown in Figure 31. The top, middle and bottom figures show the waveforms at input voltages of 12 V, 14 V and 18 V. This shows stable closed loop operation at a wide range of operating points.

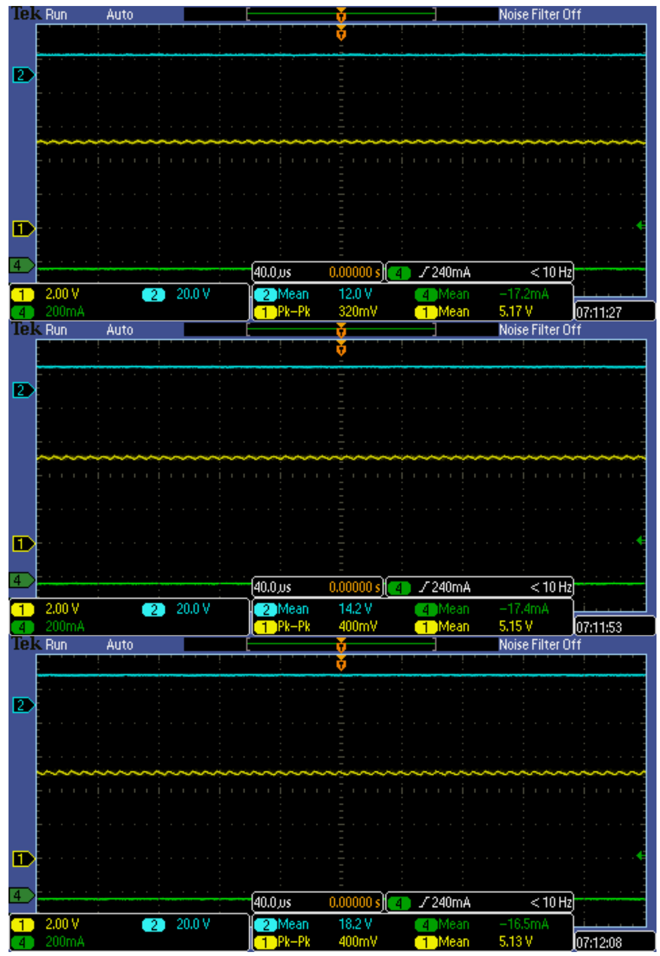

Figure 31: Stable closed-loop control in buck mode over a wide range of operating points (D=0.5, f=125 kHz, R=40 Ohm) at V_{in}=12 V (top), 14 V (middle), and 18V (bottom)

E2. *Methods to easily reach pre-set operating points for given demonstrations*

Table 3 specifies the operating points for all three modes. The duty cycle and frequency for each mode are pre-defined in the code, and the input voltage and load resistance are set to the same value for all modes. This makes the demonstration simple with minimum values to change between modes.

	V_{in} (V)	Duty cycle	Frequency (kHz)	Resistance (Ω)
Buck	5	0.7	125	40
Boost	5	0.4	100	40
Buck-boost	5	0.6	100	40

Table 3: Specified operating points for each mode of operation

Hardware Description

The test setup for this project is shown in Figure 32. It consists of an output load with four steps. The details for obtaining different resistive values are described in Table 4.

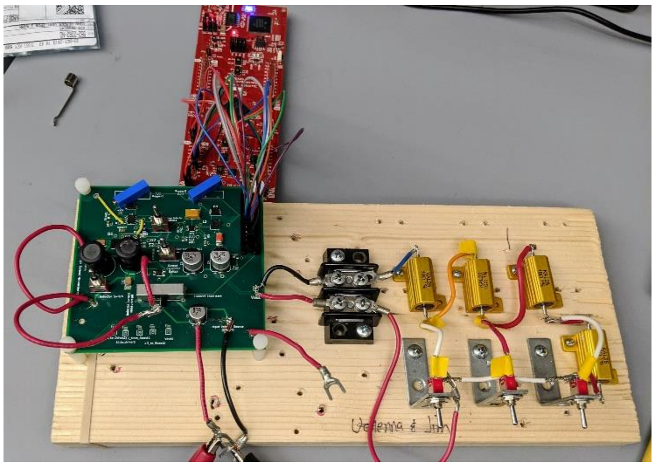

Figure 32: DC-DC converter test setup

Figure 33 shows the configuration in which resistors are arranged. The switch is turned on when the switch lever is in the down position and is off for all other positions.

Resistance (Ω)	J4	J5	J6
10	ON	-	-
20	OFF	ON	-
30	OFF	OFF	ON
40	OFF	OFF	OFF

ON - switch down
OFF - other positions

Table 4: Resistance for different switch configurations

This circuit has the capability to include two different values of inductors using switch S2. The details for choosing different inductor values are shown in Table 5. To achieve the ON position, the switch handle is turned to the left side of the circuit as shown in Figure 32.

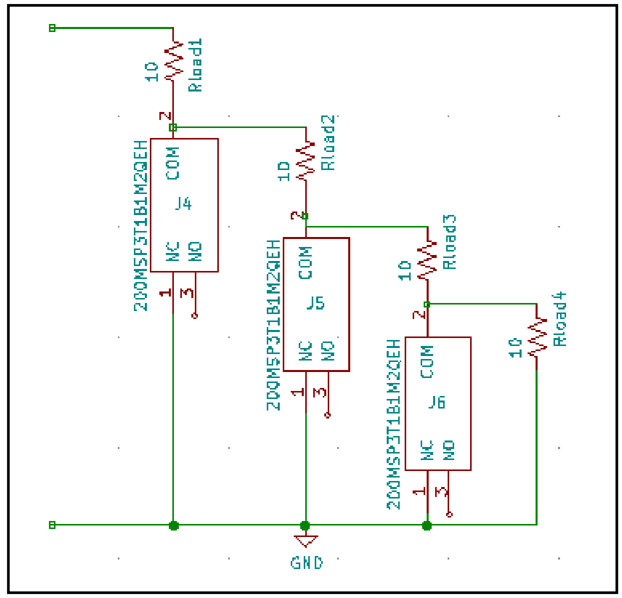

Figure 33: Schematic for load resistor

Inductance (μH)	S2
23.5	ON
47	OFF

ON - left (NC as per schematic)
OFF - other positions

Table 5: Inductance for different switch configurations

We can also achieve two different values of capacitors using switch S4. The details for choosing different capacitor values are shown in Table 6. To achieve the ON position, the switch is toggled to the right side of the circuit as shown in Figure 32.

Capacitance (μF)	S4
47	OFF
94	ON

ON - right (NC as per schematic)
OFF - other positions

Table 6: Capacitance for different switch configurations

Possible improvements

The circuit faced some issues with showing the effects of change in gate loop inductance. Thus, the gate loop section can be redesigned to ameliorate this feature. Also, closed loop current mode control can be added to make the circuit more reasonable for practical purposes.

Appendix A – Component Selection

Ref	Description	Part number	Rationale for selection
S1	4P3T switch	EG4319	Easy to switch between 3 modes (buck, boost, buck-boost)
IC1	Low Input Voltage, Step-Up DC-DC Converter for on-board boosting	LM2621MM/NOPB	Used for boosting 5 V from microcontroller to 12 V for supplying to MOSFET gates
D2	Schottky diode for on-board boost converter	MBRS140T3G	Suggested by manufacturer
D1	Bootstrap diode	CDBA540-HF	Suggested by manufacturer
CF1	Unpolarized capacitor	251R15S390JV4E	Nominal value suggested by the manufacturer
RF1	SMD resistor	PTN0805E1503BST1	Nominal value suggested by manufacturer
RFQ1	SMD resistor	PTN0805E2003BST1	Nominal value suggested by manufacturer
R4	SMD resistor	PTN0805E2003BST1	To scale output voltage by 0.02
Rgate2, Rgate1,	SMD resistor	PCAN0805E10R0BST5	Gate resistance for switch loops
Rload1, Rload2, Rload3, Rload4,	Power resistors	KAL25FB10R0	Each resistor is rated for 25W and four 10Ω resistors were used to obtain load steps 10Ω, 20Ω, 30Ω, 40Ω
Rupper1, Rupper2	Trimmer resistors	PTN0805E1502BST1	Used for varying duty cycle and frequency respectively, in open loop
C2, C10	Unpolarized capacitor	18121C105MAT2A	C2 - Power capacitor C10 - Absorbs high frequency ripples in inductor current; acts as input capacitor for boost mode

Lext1	Inductor	744762210A	To increase loop inductance
RF2	Resistor	PAT0805E1802BST1	Nominal value suggested by manufacturer
C4, C5	Power stage electrolytic capacitors	EDH476M100A9PAA	Rated for high voltages; calculated based on 4% ripple in buck mode at 200 kHz*
R1	Resistor	PTN0805E4021BST1	To sense and scale output voltage by 0.02
R3, R6	Variable resistor	T18103KT10	R3 - Duty cycle control R6 - Frequency control
R_sense1	Resistor	RL1220T-R010-J	Sensing resistor for current (peak current mode control)
Rboot1	Resistor	PATT0805L2R80FGT1	Nominal value suggested by manufacturer
C7	Unpolarized capacitor	C2012X7T2E104K125AE	Nominal value suggested by manufacturer
R5	Resistor	PTN0805E4990BST1	Nominal value suggested by manufacturer
Q2, Q1	Power stage switches	CSD19502Q5BT	MOSFETs with a safety margin in voltage limit were selected
IC2	Micropower, Single-Supply, Rail-to-Rail Precision Differential Amplifier	MAX4198EUA+	Differential amplifier to sense inductor and send to microcontroller
S3, S4, S2, J4, J5, J6	Mechanical switches	M2024SS1W01	S3 - To add/remove power inductors S4 - To add/remove power capacitors S2 - vary loop inductance
J1	Generic connector, double row, 02x10, odd/even pin numbering scheme (row 1 odd numbers, row 2 even numbers)	SBH11-PBPC-D10-ST-BK	Used for connecting jumpers from PCB to microcontroller

L3,	Inductor	744042006	Nominal value suggested by manufacturer for on board boost circuit
Jumpers	Jumpers	PRT-12796	Used for connecting PCB to microcontroller
C3	Ceramic SMD capacitor for bootstrap circuit	TMF212B7224KGHT	Nominal value suggested by manufacturer
C8	Tantalum SMD capacitor	T491D226K010AT	Nominal value suggested by manufacturer for on board boost circuit
C9	Unpolarized capacitor	595D686X0010C2T	Nominal value suggested by manufacturer for on board boost circuit
C6	Polarized capacitor	EEE-FK1H470V	Input filter capacitor
C1	Ceramic SMD capacitor for bootstrap circuit	TMF212B7105KGHT	Nominal value suggested by manufacturer for gate driver circuit
U1	Half-Bridge Gate Driver, Output Current 1.0A, 100V, SOIC-8	LM5109AMA/NOPB	Used to drive both MOSFETs as they are in the same leg
L2, L1	Power stage inductors	AIUR-06-470K	Rated for high currents; calculated based on 20% ripple in buck mode at 200 kHz*

*Calculations for power stage inductor and output capacitor:

Nominal operating point for buck mode: $D = 0.5, V_0 = 12.5\ V, R_i(current\ ripple\ ratio) = 20\%, P_0 = 25\ W, f_s = 200\ kHz, R_v(voltage\ ripple\ ratio) = 4\%$

$$L = \frac{\frac{1}{2}(1-D)\,V_0^2}{f_s R_i P_o} \approx 47\ \mu H$$

$$C = \frac{1-D}{16 f_S^2 L R_v} \approx 47\ \mu F$$