ECE 469 Lab Report - 2

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***Abstract*—Overall this report discusses two labs conducted on the topic area of DC-to-DC conversion. The buck and buck-boost converters are explored followed by converters for DC motor drives.**

I. Introduction

THIS lab focuses on DC to DC converters and it's applications. In the first part, we work on making a Buck and a Buck boost converter. In the second part, we work on using DC-DC converters as motor drives.

II. Prelab 3 and Buck Converter Theory

Consider the circuit for a buck converter as shown in Fig. 1 below.

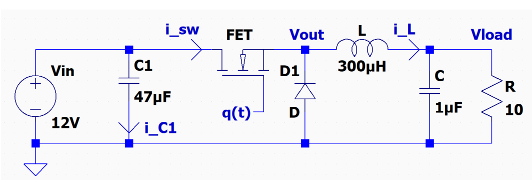

Fig. 1: Buck converter circuit in Prelab 3 [1].

This DC-DC converter is used to step down voltages from the input (Vin) to the output (Vload). For the analysis in Prelab 3, we shall assume a resistor load of 10 Ω and a duty cycle $D = 0.3$. This duty cycle indicates that ratio of time the MOSFET gate signal q(t) is 1 to the total period T of q(t).

The first step in analyzing this circuit is finding the voltage conversion ratio; this can be accomplished by using the periodic steady state condition for an inductor $< v_L >= 0$. The voltage across the inductor L is shown in Fig. 2 below.

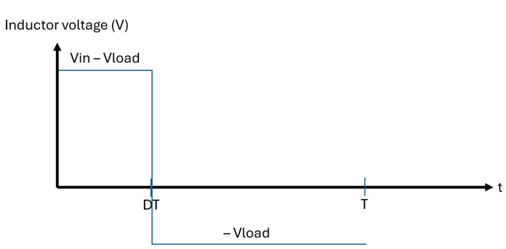

Fig. 2: Inductor voltage waveform.

Solving for average voltage and equating it to zero, we have:

$$D(V_{in} - V_{load}) + (1 - D)(-V_{load}) = 0$$

which simplifies to:

$$V_{load} = DV_{in}$$

If we assume the output capacitor C is large, the output current is approximately given by:

$$< i_R >= \frac{V_{load}}{R} = \frac{DV_{in}}{R}$$

and by average KCL, we find that $< i_L >=< i_R >$ since no DC current passes through C during P.S.S.

To fully characterize the inductor current, we also need to find the current ripple. To do so, we inspect Fig. 2 to find the voltage across the inductor and time interval during which it charges. For the interval when the MOSFET is on, the rate of change in the inductor current is given by:

$$\frac{di}{dt} = \frac{v_L}{L} = \frac{V_{in} - V_{load}}{L} = 28\ kA/s$$

The total change in current during this interval will be the product of $\frac{di}{dt}$ and $DT = 3\ \mu s$. We find that $\Delta i_L = 84\ mA$. Using the current ripple and the average current through the inductor, we can plot the waveform shown in Fig. 3.

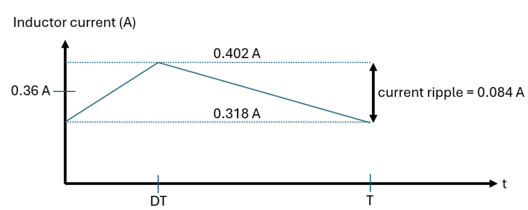

Fig. 3: Inductor current waveform.

The output voltage ripple across capacitor C can be found by assuming that the ac component of $i_L(t)$ passes completely through C. Subtracting the average inductor current from the waveform in Fig. 3, we get the output capacitor current waveform as shown in Fig. 4. Next, we can integrate the positive portion of this waveform to get the total amount of charge Q that accumulates during this interval.

We know that the average capacitor current must be zero, by P.S.S., therefore the charge into the capacitor during the positive current interval must equal to charge removed during

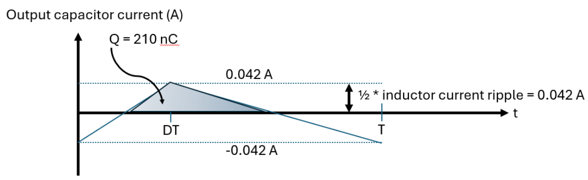

Fig. 4: Output capacitor current waveform.

the negative current interval. Therefore, the total output capacitor voltage ripple Δv_c is determined by this charge using the relationship $Q = CV$ for a capacitor. Solving for Δv_c, we have:

$$\Delta v_c = Q/C = 210\ mV$$

In addition, we can plot the voltage across the diode (also known as the switch node voltage). In this case, the voltage across the diode is denoted by v_{out}. Using KVL and noting that the FET is on for $t \in [0, DT]$ and the diode is on for $t \in [DT, T]$, we can simply plot the V_{out} waveform as shown in Fig. 5.

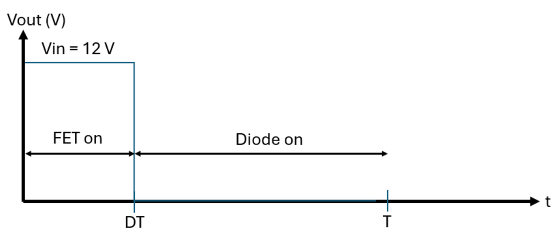

Fig. 5: Voltage at the switch node.

When the FET is on, $V_{out} = V_{in}$. Otherwise it is equal to zero.

Finally, we can analyze the voltage ripple across the input capacitor. This analysis is similar to that for the output capacitor; however, in this case we must determine input current passing through the FET. This current is denoted i_{sw} in the circuit diagram (Fig. 1). Note that when the FET is on, $i_{sw} = i_L$ otherwise $i_{sw} = 0$. Thus, using the previously determined inductor current waveform we can fully characterize the FET current.

A similar assumption must be made about the ac current component. We assume that the DC part of i_{sw} passes completely through the source, while the ac part passes completely through input capacitor C1. By KCL, we find that $\tilde{i}_{sw} = i_{C1}$. The ac component of the FET input current is sketched in Fig. 6 below. We can again integrate the current to find the total charge accumulation. This charge Q is noted in Fig. 6. Although there is a sign difference between i_{C1} and $\tilde{i}_{sw}$, this does not affect the charge calculation.

Finally, the peak-to-peak input voltage ripple across C1 is given by:

$$\Delta v_{C1} = Q/C_1 = 16.09\ mV$$

III. Discussion of Lab 3

Lab three was divided into two main parts. First, a buck converter was assembled, followed by a buck-boost converter.

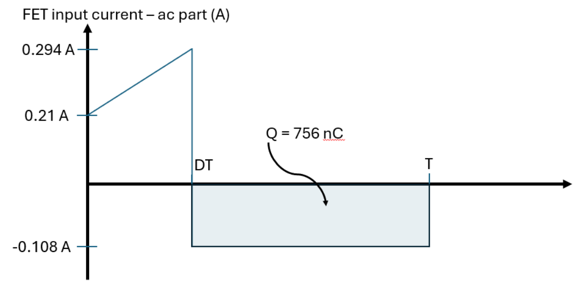

Fig. 6: Input ac current $\tilde{i}_{sw}$ into FET.

A buck converter is a DC-DC converter used to step down voltages (e.g., suitable for computer power supply units). In contrast, a buck-boost converter is capable of decreasing and increasing its output voltage with respect to its input. This added flexibility makes the buck-boost converter versatile in applications such as regulating the voltage from a battery.

This experiment used the FET boxes available on each lab bench. The FET box contains two MOSFETs and two diodes. Gate drive circuity is included internally within the FET box for simplicity; duty cycle and switching frequency can be adjusted easily using potentiometer knobs.

A. *methods for part 1*

A sketch of the buck converter circuit and measurement connections is shown in Fig. 7

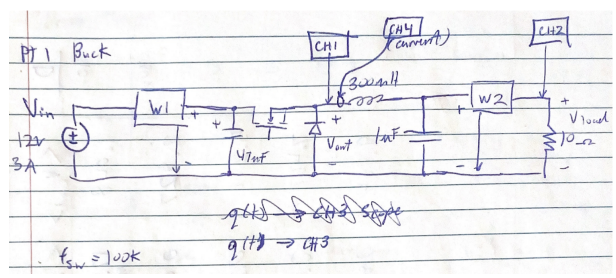

Fig. 7: Sketch of buck converter circuit and measurement points.

The Keithly bench power supply was set to output 12V at a maximum current of 3A. This voltage source was used as the input V_{in}. The load was taken to be a 10 Ω resistor; a discrete power resistor was used. The inductor and capacitor were chosen to be 300 μH and 1 μF respectively.

The input capacitor was a 47 μF tantalum capacitor. It was important to connect this capacitor physically close to the FET box in order to minimize parasitic stray inductance.

The following instruments were used for taking measurements. The two Yokogawa Wattmeters were connected across the input and output ports to measure RMS current, voltage, and power. The Tektronix scope was connected with CH1 measuring V_{out}, CH2 measuring V_{load}, CH3 measuring the switching signal $q(t)$ from the FET box, and CH4 measuring the inductor current via a current probe.

Initially, the switching frequency was set to 100 kHz. Switch node and load voltage waveforms were recorded for a duty cycle of 50%. Output voltage ripple waveforms $\tilde{v}_{load}$ were recorded for $D \in \{0.1,\ 0.5,\ 0.9\}$.

Tabular measurements were taken for a range of duty cycles $D \in \{0.1,\ 0.3,\ 0.5,\ 0.7,\ 0.9\}$. Average load voltage, average input current, average input power, average output power, $V_{in(rms)}$, $I_{in(rms)}$, $V_{load(rms)}$, and $I_{load(rms)}$ were recorded.

Lastly, the rate of change in inductor current $\frac{di}{dt}$ was measured at a reduced switching frequency of $f_{sw} = 5\ kHz$. As discussed in our results section, this data was used to estimate the inductance using the relationship $v_L = L\frac{di}{dt}$. Assuming small voltage ripple, the voltage across the inductor during any given switch state should be nearly constant.

B. methods for part 2

A sketch of the buck-boost circuit and measurement connections is shown in Fig. 8

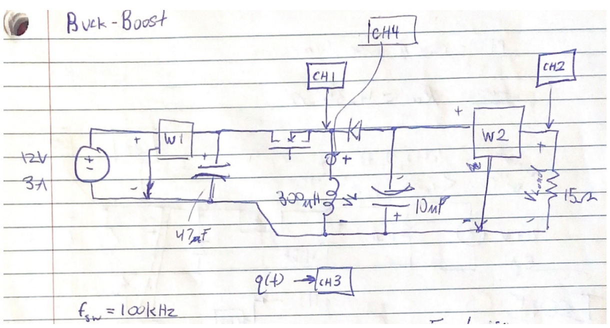

Fig. 8: Sketch of buck converter circuit and measurement points.

Similar to the buck converter circuit, the Keithly power supply was used with a 12V output for the source V_{in}. The same inductor and a new output capacitor (10 μF) were used. A new load resistance of 15 Ω was used.

The following instruments were used for measurements. Yokogawa Wattmeters were again used to measure RMS voltage, current, and power on the input and output ports of the converter. The Tektronix scope was connected with CH1 measuring the voltage across the inductor v_L, CH2 measuring the output voltage v_{load}, CH3 measuring $q(t)$, and CH4 measuring the inductor current.

Waveforms for the buck-boost converter were measured at $D = 0.5$. Using the scope, $v_L(t)$, $i_L(t)$, and $\tilde{v}_{load}(t)$ were recorded. AC coupling was used to measure the ripple waveform.

Tabular data was recorded at the following duty cycles $D = \{0.2,\ 0.4,\ 0.5,\ 0.6,\ 0.65\}$. Average load voltage, $V_{load(rms)}$, average input current, and $I_{in(rms)}$ were recorded. Power measurements were not recorded for these duty cycles.

C. Lab 3 results

Buck converter waveforms are shown in the following figures. In Fig. 9 the $v_{out}(t)$ and $v_{load}(t)$ waveforms are shown for the case $D = 0.5$. In Fig. 10 the ac component of the output voltage $\tilde{v}_{load}$ is shown, which gives the output voltage ripple waveform.

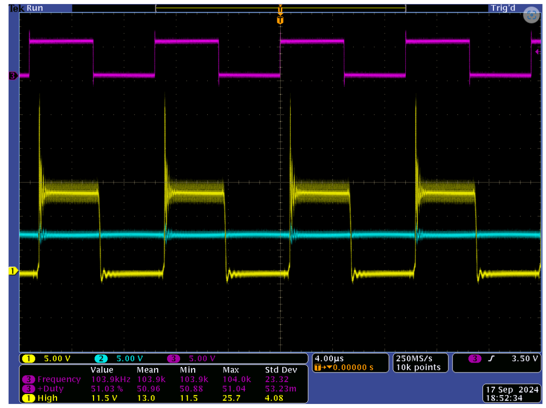

Fig. 9: Buck converter waveforms for v_{load} (CH2) and v_{out} (CH1) at $D = 0.5$.

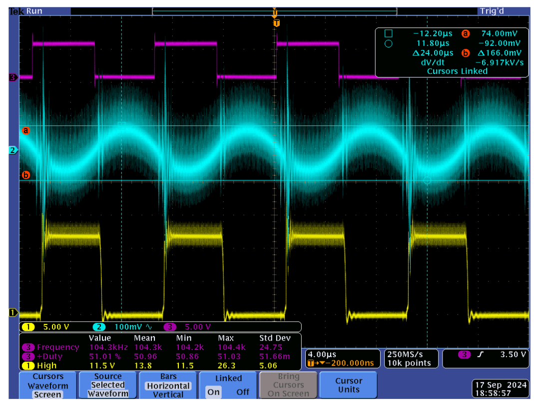

Fig. 10: Buck converter $\tilde{v}_{load}$ (CH2) for $D = 0.5$.

The ripple signal has considerable noise, so the cursors were used to measure the peak-to-peak ripple. It was found that for $D = 0.5$, $\Delta v_{load} = 166\ mV$.

The inductor current $\frac{di}{dt}$ was measured at a reduced switching frequency of $f_{sw} = 5\ kHz$, as shown in Fig. 11.

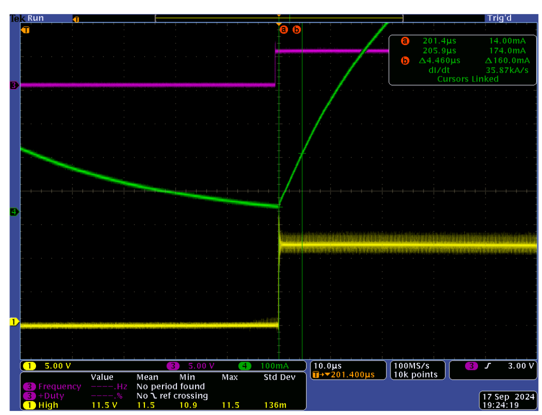

Fig. 11: Buck converter inductor $\frac{di}{dt}$ measurement at $D = 0.5$.

The rate of change of current was measured to be $\frac{di}{dt} = 35.87\ kA/s$. At $D = 0.5$, we also measured $< V_{load} >= 5.211\ V$. Neglecting voltage drop across the FET and assuming small output votlage ripple, we can find the inductor voltage v_L as:

$$v_L = V_{in} - < V_{load} > = 6.789\ V$$

Next, we can approximate the inductance as:

$$L = v_L \left(\frac{di}{dt}\right)^{-1} = 189.267\ \mu H$$

We can use this inductance value to estimate the output voltage ripple Δv_C. From the Prelab analysis, we found that:

$$\Delta v_C = \frac{Q}{C} = \frac{T \Delta i_L}{6C}$$

We can calculate Δi_L for $D = 0.5$ as follows:

$$\Delta i_L = DTv_L/L$$

where v_L is the voltage across the inductor when the FET is on (assuming small ripple on v_{load}). Thus, we have: $\Delta i_L = 179.35\ mA$ and finally $\Delta v_c = 298.92\ mV$.

Compared to the actual measured output ripple, this estimated value is much higher (by 165 mV). Not that the inductance used for the calculation was much lower than the expected value of 300 μH, so it is possible that the inductance was incorrectly calculated due to an erroneous $\frac{di}{dt}$ measurement. The larger the inductor the lower the current ripple. Since the output voltage ripple is directly proportional to the current ripple, a larger inductor also reduces the output voltage ripple. [1]

The measured waveforms for the buck-boost converter are as follows. Fig. 12 shows the switching signal, inductor voltage and current, and output voltage. In addition, Fig. 13 shows the output voltage ripple.

Fig. 12: Buck-boost converter waveforms: CH1 $v_L(t)$, CH2 $-v_{load}(t)$, CH3 $q(t)$, CH4 $i_L(t)$.

Note that the output voltage is the opposite polarity compared to the input voltage; in Fig. 12, the output voltage signal is inverted.

According to Fig. 13, the output voltage ripple $\Delta v_{load} = 1.08\ V$.

The tabular results for the buck converter are presented in Table I below.

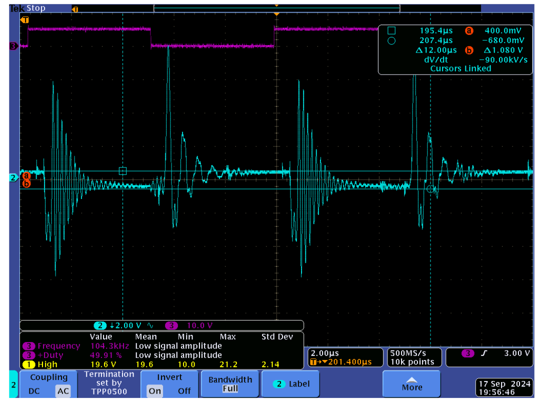

Fig. 13: Buck-boost converter output voltage ripple.

Measurements for the buck-boost converter are presented in Table II.

Note that the RMS values for v_{load} as well as the average values are almost identical in terms of magnitude. For the case of the buck-boost converter, the average load voltage is negative so it will differ from the RMS load voltage. We expect that the magnitude of these voltages will be similar because the ripple is small. [2]

Given the input and average output voltage, we can calculate the voltage conversion ratio $M =< V_{load} > /V_{in}$. For an ideal buck and buck-boost converter, we expect M to be a function of duty cycle as follows.

buck-boost:

$$M(D) = -\frac{D}{1-D}$$

buck:

$$M(D) = D$$

Using the measured data, the experimental voltage conversion ratios were calculated. Table III and Table IV show the experimentally determined conversion ratio M_e and theoretical ideal conversion ratio M_t for the buck-boost and buck converter respectively.

Furthermore, the voltage conversion ratios for both converters were plotted in Fig. 14. As shown by the figure, the actual voltage conversion ratios were lower in magnitude compared to the ideal cases. This makes sense because practical converters exhibit conduction and switch losses which will reduce the absolute value of the output voltage. [3]

Finally, efficiency for both converters was calculated using the input and output power. In general, efficeincy η is given by:

$$\eta = \frac{P_{out}}{P_{in}}$$

In the case of the buck converter, both of these quantities were directly measured using the Wattmeters. For the buck-boost converter, we had to estimate the input and output power using RMS quantities. Output power was assumed to be:

$$P_{out} \approx V_{load(rms)}^2/R$$

[1]Answer to study question 4 from lab 3.
[2]Answer to study question 1 from lab 3
[3]Answer to study question 2 in lab 3

TABLE I: Tabular measurements for the buck converter.

D	$< V_{load} >$ (V)	$< I_{in} >$ (A)	$< P_{in} >$ (W)	P_{out} (W)	$V_{in(rms)}$ (V)	$I_{in(rms)}$ (A)	$V_{load(rms)}$ (V)	$I_{load(rms)}$ (A)
0.1	1.048	1.73E-02	0.208	0.102	11.989	1.74E-02	1.048	9.75E-02
0.3	2.927	0.09	1.07	0.836	11.968	0.089	2.928	0.286
0.5	5.211	0.25	3.028	2.648	11.918	0.254	5.212	0.508
0.7	7.467	0.5	5.96	5.435	11.84	0.503	7.453	0.727
0.9	9.984	0.86	10.03	9.726	11.7	0.855	9.796	0.955

TABLE II: Tabular measurements for the buck-boost converter.

D	$< V_{load} >$ (V)	$V_{load(rms)}$ (V)	$< I_{in} >$ (A)	$I_{in(rms)}$ (A)
0.2	-2.33	2.33	0.05	0.045
0.4	-5.96	5.971	0.26	0.255
0.5	-8.592	8.603	0.536	0.537
0.6	-11.83	11.81	1.08	1.08
0.65	-13.69	13.72	1.51	1.51

TABLE III: Voltage conversion ratio for buck-boost converter, experimental and ideal.

D	M_e	M_t
0.2	-0.194166667	-0.25
0.4	-0.496666667	-0.666666667
0.5	-0.716	-1
0.6	-0.985833333	-1.5
0.65	-1.140833333	-1.857142857

The results for the efficiency calculations are shown in Tables V and VI and in Fig. 15.

As shown in Fig. 15, the buck converter has higher efficiency as you increase duty cycle, whereas the buck-boost converter decreases in η as duty cycle is increased. At $D = 0.4$, the buck-boost converter exhibited its highest efficiency of $\eta = 77.7\%$ [4]

IV. Discussion of Lab 4

This experiment was divided into two parts. In the first part,we make a class-A motor drive. In the second part, we make a class-C chopper circuit motor drive.

A. Theory

1) Part-1 : Class-A motor drives: Figure 16, shows the simplified version of the circuit. In this simplified version, the protection of the source voltage is removed. Where, L_a is the armature inductance of the DC machine, R_a is the armature resistance and E is the back emf of the DC motor.

Seeing that the circuit is a DC-DC buck converter, we can say that the average motor voltage (V_t) will be as follows.

[4]Answer to study question 3 from lab 3

TABLE IV: Voltage conversion ratio for buck converter, experimental and ideal.

D	M_e	M_t
0.1	0.087413462	0.1
0.3	0.24456885	0.3
0.5	0.437237792	0.5
0.7	0.630658784	0.7
0.9	0.853333333	0.9

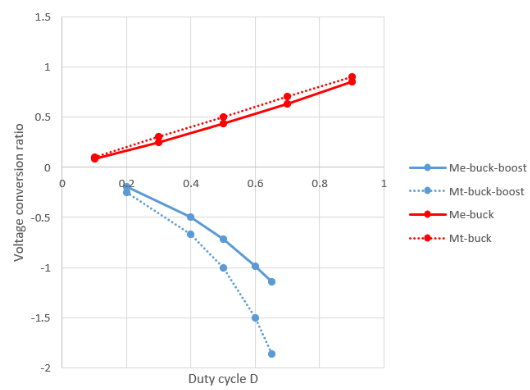

Fig. 14: Comparison of voltage conversion ratios between ideal (M_t) and measured (M_e)

TABLE V: Efficiency for the buck converter

D	η
0.1	0.490384615
0.3	0.781308411
0.5	0.874504624
0.7	0.911912752
0.9	0.969690927

$$< V_t > = DV_{in}$$

Where D is the duty ratio of the switch S and V_{in} is the input voltage. From this we see that the average motor voltage ($< V_t >$) is determined by the duty ratio (D)[5]. From the circuit and this we would get the average output current ($< I_{out} >$) as follows.

$$\begin{aligned} < I_a > &= \frac{< V_t > - E_a}{R_a} \\ &= \frac{DV_{in} - E_a}{R_a} \end{aligned}$$

From this we can say that the motor voltage ($V_t(t)$) is equal to the back emf of the motor when the armature current (I_a) is 0[6]. To find the peak-to-peak ripple of the armature current (ΔI_a), we find the equation of the armature current ($I_a(t)$). The equation of $I_a(t)$ when switch S is ON is as follows[7].

$$I_a(t) = \frac{(V_{in} - E)}{R_a} + (I_{a_{min}} - \frac{(V_{in} - E)}{R_a})e^{-\frac{R_a}{L_a}t}$$

The equation of $I_a(t)$ when switch S is OFF is as follows[8].

[5]Answer to Study Question - 4
[6]Answer to Study Question - 1
[7]Solution to Pre-Lab Question - 2
[8]Solution to Pre-Lab Question - 2

TABLE VI: Efficiency for the buck-boost converter

D	η
0.2	0.670234568
0.4	0.776750349
0.5	0.765690141
0.6	0.71746965
0.65	0.692562178

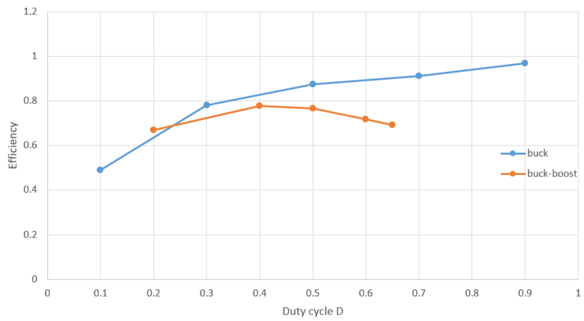

Fig. 15: Efficiency comparison between buck and buck-boost converter.

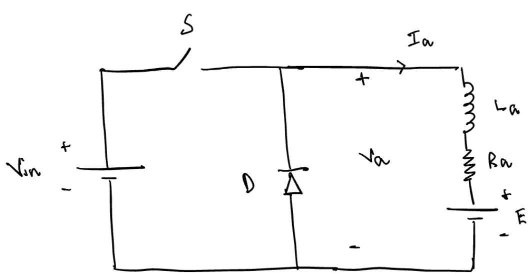

Fig. 16: Simple circuit diagram of Class-A motor drive.

$$I_a(t) = -\frac{E}{R_a} + (I_{a_{max}} + \frac{E}{R_a})e^{-\frac{R_a}{L_a}t}$$

Where f_{sw} is the switching frequency. Differentiating the equation of armature current ($I_a(t)$) when the switch is OFF, we get the following.

$$\frac{dI_a}{dt}(t) = -\frac{R_a}{L_a}(I_{max} + \frac{E}{R_a})e^{-\frac{R_a}{L_a}t} \tag{1}$$

Using this we can find the value of the armature inductance (L_a).

2) Part-2 : Class-C motor drives: Figure 16, shows the simplified version of the circuit. In this simplified version, the protection of the source voltage is removed. The difference between Class-A and Class-C motor drives is that in class-A there is a free-wheeling diode and in Class-C this diode is replaced by a transistor that allows the current to flow through it in both the directions.

Here, the switches S1 and S2 are given complimentary switching signals with the same frequency but with a dead-time. This deadtime is needed becuase, if not present, then the source voltage would get short circuited when both the

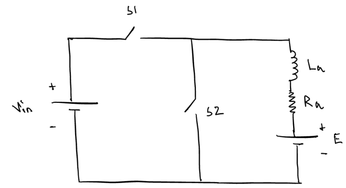

Fig. 17: Simplified circuit diagram of Class-C motor drive.

switches are ON [9]. In this circuit, the average motor voltage ($< V_t >$) and the average armature current ($< I_a >$) are the same as in Class-A motor drive. The equation of the armature current ($I_a(t)$) is also the same as in Class-A motor drive. But, the armature current ($I_a(t)$) and the average armature current ($< I_a >$) can be negative in this case.

B. Lab Results

We first measure the armature resistance (R_a) of the DC motor using a multimeter. We found it to be equal to 4.35 Ω.

1) Part-1 : Class-A motor drive: We construct the circuit as shown in Figure-18.

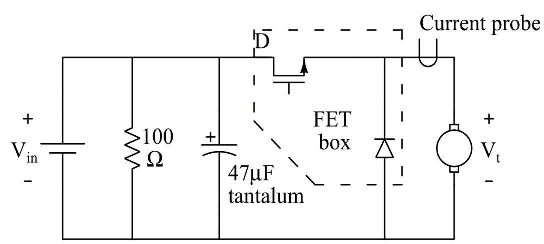

Fig. 18: Class-A chopper circuit [1]

We set the input voltage (V_{in}) as 24 V. The maximum switching frequency to which the FET box could reach was 17.92 KHz. So instead of setting it at 20 KHz, we set the switching frequency of the FET box at 17.92 KHz. The least duty ratio (D) for which the motor starts rotating is 7.8%. Refer to Table-VII for the average armature current ($< I_a >$), average motor voltage ($< V_t >$) and the peak-to-peak value of the armature current(ΔI_a) for different duty ratios (D). Refer to Figure-19, 20 and 21 for the waveforms obtained for motor voltage (V_t) and armature current (I_a) for different duty ratios (D).

D(%)	$< I_a >$(A)	$< V_t >$(V)	ΔI_a (A)
7.8	0.9	1.08	0.72
50	1.35	10.65	1.28
90	1.43	20.55	0.88

TABLE VII: Measured armature currents and motor voltages for different duty ratio.

Reducing the switching frequency (f_{sw}) to 2 KHz and keeping the duty ratio (D) as 50% we get the waveforms for motor voltage (V_t) and armature current (I_a) as shown in Figure-22.

During the time when the switch S is OFF, the armature current (I_a) drops to 0. It cannot go negative because the

[9]Answer to Study Question-6

Fig. 19: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 7.8\%$ and $f_{sw} = 20$ KHz.

Fig. 20: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 50\%$ and $f_{sw} = 20$ KHz.

Fig. 21: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 90\%$ and $f_{sw} = 20$ KHz.

diode cannot conduct reverse current. This is the reason why class-A choppers cannot be used for regeneration[10]. Using the $\frac{dI_a}{dt}$ during the time when the armature current (I_a) is falling, we can get the value of the armature inductance (L_a). From

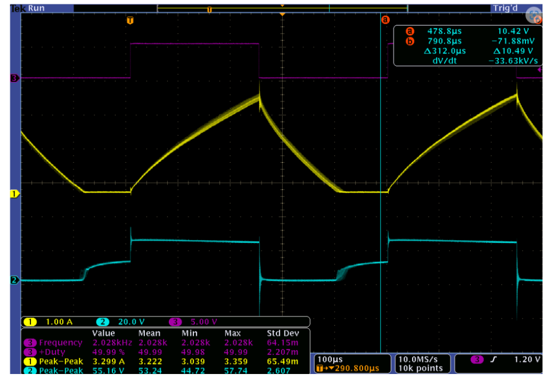

Fig. 22: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 50\%$ and $f_{sw} = 2$ KHz.

Figure-22, we see that the back emf of the DC motor (E) is 10.42 V. We also see from Figure-22 that the maximum armature current ($I_{a_{max}}$) is 3.04 A. We find that the $\frac{dI_a}{dt}$ at time t = 7.8 μs after the switch is OFF, as -22.2 KA/s. Placing these in equation-(1), we get the following.

$$-22.2 \times 10^3 = -\frac{4.35}{L_a}(3.04 + \frac{10.42}{4.35})e^{-\frac{4.35}{L_a} \times 7.8 \times 10^{-6}}$$

Solving the above equation using MATLAB, we get the armature inductance (L_a) as 1.03 mH [11].

As we know the value of the back emf of the motor (E), we can calculate the average power transfered to the motor shaft ($< P_{shaft} >$) by using the following equation.

$$< P_{shaft} > = E < I_a > \tag{2}$$

Using this we find the average power transfered to the shaft of the motor ($< P_{shaft} >$) for different duty ratios for switching frequency (f_{sw}) of 17.92 KHz as shown in Table-VIII[12].

D(%)	$< P_{shaft} >$(W)
7.8	9.378
50	14.067
90	14.872

TABLE VIII: Calculated average power transfered to the shaft of the motor ($< P_{shaft} >$) for different duty ratios (D) at $f_{sw} = 17.92$ KHz.

2) Part-2 : Class-C motor drive: We construct the circuit as shown in Figure-23.

We set the input voltage (V_{in}) as 24 V. We set the switching function of the second FET to q' and the switching frequency to 17.92 KHz (This is the maximum switching frequency that could be set in our FET box).Running this circuit at a duty ratio (D) of 50%, we get the results as shown in Table-IX

[10]Part of the answer to Study Question-5

[11]Answer to Study Question-3

[12]Answer to Study Question-2

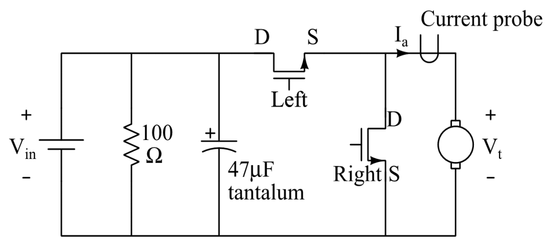

Fig. 23: Class-C chopper circuit. [1]

$< I_a >$(A)	$< V_t >$(V)	ΔI_a(A)
1.11	5.33	1.47

TABLE IX: Measured average armature current ($< I_a >$), average motor voltage ($< V_t >$) and peak-to-peak ripple of the armature current (ΔI_a) at a duty ratio (D) of 50%.

We get the waveform of the armature current (I_a) and motor voltage (V_t) for the duty cycle (D) of 50% as shown in Figure-24.

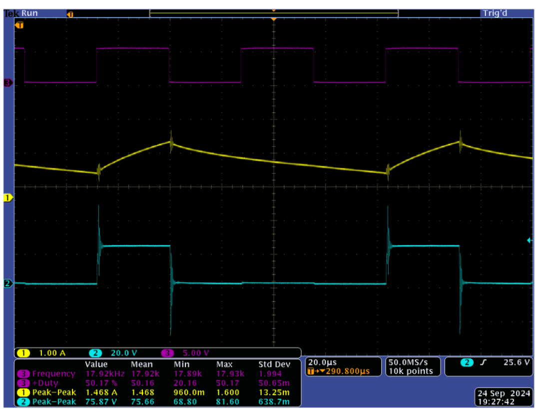

Fig. 24: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 50\%$ and $f_{sw} = 17.92$ KHz.

We then increase the duty ratio (D) to 73 % keeping the switching frequency (f_{sw}) as 17.92 KHz. Then we suddenly turn the shaft of the motor in the reverse direction and take a snapshot of the waveforms generated in the oscilloscope. The snapshot of the armature current (I_a) and the motor voltage (V_t) is shown in Figure-25.

From Figure-25, we see that the armature current (I_a) is negative. The back emf generated would also be negative because the motor shaft is rotated in the opposite direction. From this we can say that the motor acts as a generator in this case.

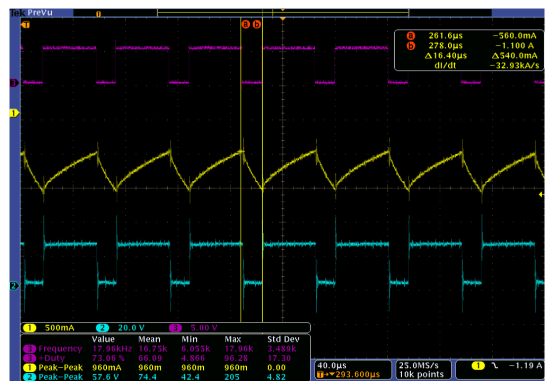

Fig. 25: Waveform of switching signal of the FET box (q), armature current (I_a) and motor voltage (V_t) for $D = 73\%$ and $f_{sw} = 17.92$ KHz when shaft rotated in the reverse direction.

V. Conclusion

Overall, we gained deeper insights into DC-DC converters, particularly how varying duty cycle affects the behavior of the converter, including its efficiency. In addition we learned about the application of DC motor drivers.

References

[1] ECE 469 lab manual