ECEN 438/738 – Power Electronics Spring 2025

Lab 4: Buck Converter: Filter Design

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The goal of this lab is to investigate the L-C filter operation in a Buck regulator. In particular, we analyze the behavior of the L-C filter subjected to the square-wave voltage generated by a PWM modulated MOSFETs half-bridge. First, we review the function and the principle of operation of the inductor and of the capacitor in the L-C filter of a buck regulator, to predict the inductor current ripple and the output voltage ripple. Then, we simulate a buck regulator comprised of a MOSFET half-bridge, a PWM modulator, an L-C filter and a load resistor, to verify the consistency of theoretical predictions under different operating conditions. Finally, we perform lab experiments to measure the average output voltage, current and voltage ripple, and efficiency of a buck regulator in open loop operation, and to estimate the parameters of the L-C filter.

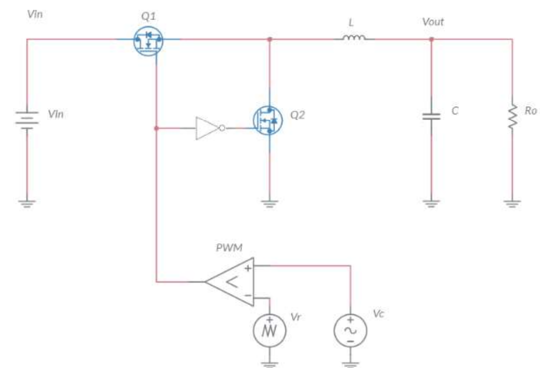

Figure 1-1 Buck Regulator with L-C Filter

Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Given a PWM modulated MOSFET half-bridge, an L-C filter, a source voltage, and a load resistance, you will calculate the peak-peak amplitude of inductor ripple current and output ripple voltage, and the converter efficiency, with specified units and accuracy, by applying the appropriate theoretical equations.
2. Given a PWM modulated MOSFET half-bridge, an L-C filter, a source voltage, and a load resistance, you will simulate the L-C filter behavior to verify the consistency of theoretical predictions, by comparing the simulated and the calculated output voltage under the same operating conditions.
3. Given a real PWM modulated MOSFET half-bridge, an L-C filter, a source voltage, a load resistance, and a two channel function generator, you will measure the converter efficiency and the peak-peak amplitude of inductor ripple current and output ripple voltage, and you will determine the parameters of the inductor and of the capacitor, with specified units and accuracy.

Required Tools and Technology

Platform: NI ELVIS III Instruments used in this lab: • Function generator • Digital multimeter • Oscilloscope • Power Supply **Note**: The NI ELVIS III Cables and Accessories Kit (purchased separately) is required for using the instruments.	✓ Access Instruments https://measurementslive.ni.com/ ✓ View User Manual http://www.ni.com/en-us/support/model.ni-elvis-iii.html ✓ View Tutorials https://www.youtube.com/watch?v=TwvbRUpEpJU&list=PLvcPIuVaUMIWm8ziaSxv0gwtshBA2dh_M
Hardware: TI Power Electronics Board	✓ View User Manual http://www.ni.com/en-us/support/model.ti-power-electronics-board-for-ni-elvis-iii.html
Software: NI Multisim Live	✓ Access https://www.multisim.com/ ✓ View Tutorial https://www.multisim.com/get-started/
Software: TI Power Electronics Configuration Utility	✓ Download (Windows OS Only) http://download.ni.com/support/acadcw/PowerElectronics/TIPowerElectronicsBoardUtility-Windows.zip Note: Mac Version will be available soon

Expected Deliverables

In this lab, you will collect the following deliverables:

- ✓ Calculations based on equations provided in the Theory and Background Section
- ✓ Results of circuit simulations performed by NI Multisim Live
- ✓ Results of experiments performed by means of TI Power Electronics Board for NI ELVIS III
- ✓ Observations and comparisons on simulations and experimental results
- ✓ Questions Answers

Your instructor may expect you to complete a lab report. Refer to your instructor for specific requirements or templates.

1 Theory and Background

1-1 Introduction

In this section, we review the fundamental concepts relevant to the operation of the L-C filter in a Buck regulator. The L-C filter is an important functional element of DC-DC voltage regulators, as it integrates energy transfer and noise filtering features.

1-2 Ideal L-C filter operation in the Buck Regulator.

Figure 1-2 shows a MOSFETs half-bridge controlled by a Pulse Width Modulation (PWM) comparator. The carrier signal V_r, and the control signal V_c determine the status of the PWM comparator output. During the time T_{on} we have $V_r < V_c$ and the PWM comparator output is high. Therefore, the Gate Driver sets gate signals G1 and G2 respectively high and low, thus Q1 conducts and Q2 is open. During the time T_{off} we have $V_r > V_c$ and the PWM comparator output is low. Therefore, the Gate Driver sets gate signals G1 and G2 respectively low and high, thus Q1 is open and Q2 conducts. This results in the square-wave half-bridge output voltage V_{out} shown in Figure 1-2. The switching frequency $f_s = 1/T_s$ is determined by the period T_s of the triangular signal V_r.

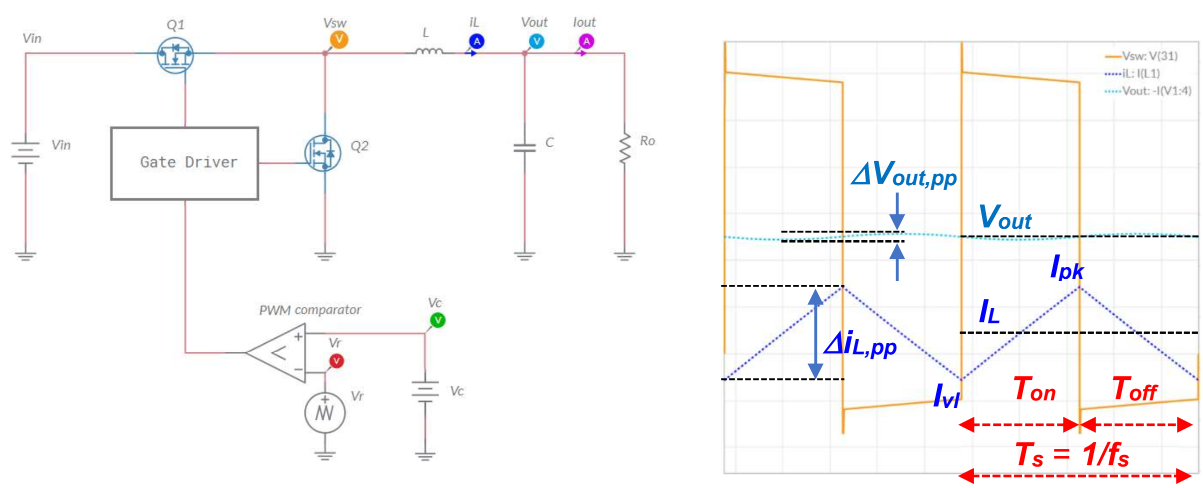

Figure 1-2. Buck Regulator L-C Filter Operation.

The typical waveforms of output voltage and the inductor current of buck regulator in open loop DC operation are shown in Figure 1-2. The peak-peak amplitude of the output voltage AC component $\Delta V_{out,pp}$, defined as *output ripple voltage*, is normally very small compared to the average DC component V_{out} (typically, $\Delta V_{out,pp}$ is about 1% of V_{out}), and the output voltage waveform is almost flat. The average DC component I_L of the inductor current equals the average load current $I_{out} = V_{out} / R_o$, as the DC current of the output capacitor is zero. The voltage V_{sw} of the half-bridge is a square wave, switching between V_{in} during the MOSFET Q1 on time T_{on} and zero during the MOSFET Q1 off time T_{off} (see **Lab5** for more details about half-bridge PWM operation). As a consequence, the inductor voltage is a square wave too, switching between V_{in} - V_{out} and - V_{out}. The resulting AC component of the inductor current, defined as *inductor ripple current*, is the triangular waveform with peak-peak amplitude $\Delta i_{L,pp}$ shown in Figure 1-2. The capacitor bypasses the inductor ripple $\Delta i_{L,pp}$. Due to the low pass nature of the L-C filter, the DC average value V_{out} of the capacitor voltage equals the average value of the half-bridge square-wave voltage, $V_{out} = V_{sw,DC} = V_{in}\text{x}D$, where D is the duty-cycle of the half-bridge, defined as $D = T_{on} / (T_{on} + T_{off}) \cong V_{out}/V_{in}$ (see **Lab5**). The resulting theoretical peak-peak amplitudes of inductor ripple current and output ripple voltage are given by Equations 1-1:

Equations 1-1

$$\Delta i_{L,pp} = \frac{D(V_{in} - V_{out})}{f_s L} = \frac{V_{out}(V_{in} - V_{out})}{V_{in} f_s L} \qquad \Delta V_{out,pp} = \frac{\Delta i_{L,pp}}{8 f_s C}$$

where f_s is the switching frequency, L is the inductance of the inductor and C is the capacitance of the capacitor. The peak-peak amplitude of inductor ripple current $\Delta i_{L,pp}$ is normally comparable to the DC component I_L (typically, it is about 50% of I_L). Equations 1-1 and 1-2 show that:

a. given the switching frequency f_s, the DC input voltage V_{in} and the DC output voltage V_{in}, the peak-peak amplitude of the inductor ripple current $\Delta i_{L,pp}$ is bigger if the inductance L is smaller;

b. given the switching frequency f_s and the inductor ripple current $\Delta i_{L,pp}$, the peak-peak amplitude of the capacitor ripple voltage $\Delta v_{out,pp}$ is bigger if the capacitance C is smaller;

c. given the DC input voltage V_{in}, the DC output voltage V_{in}, the inductance L and the capacitance C, the peak-peak amplitude of inductor ripple current $\Delta i_{L,pp}$ and capacitor ripple voltage $\Delta v_{out,pp}$ is smaller if the switching frequency is higher.

From Equations 1-1 we can derive the values of the inductance L and capacitance C needed to obtain a desired inductor ripple current $\Delta i_{L,pp}$ and capacitor ripple voltage $\Delta v_{out,pp}$, given the DC input voltage V_{in}, the DC output voltage V_{in} and the switching frequency f_s:

Equations 1-2

$$L = \frac{V_{out}(V_{in} - V_{out})}{V_{in} f_s \Delta i_{L,pp}} \qquad C = \frac{\Delta i_{L,pp}}{8 f_s \Delta V_{out,pp}}$$

1-3 Effects of MOSFET, inductor and capacitor resistance.

Real MOSFETs, inductors and capacitors have a parasitic resistance, causing power losses and influencing the inductor ripple current and capacitor ripple voltage. The ohmic power losses of MOSFET, inductor and capacitor are given by Equations 1-3:

Equations 1-3
$$P_{Q1} = R_{ds(on)}^{Q1} D I_L^2 \alpha;\; P_{Q2} = R_{ds(on)}^{Q2} (1-D) I_L^2 \alpha;\; P_L = R_L I_L^2 \alpha;\; P_C = R_C \frac{\Delta i_{Lpp}^2}{12};\; \alpha = \left(1 + \frac{\Delta i_{Lpp}^2}{12 I_L^2}\right)$$

where $R_{ds(on)}^{Q1}$ and $R_{ds(on)}^{Q2}$ are the On-State resistances of MOSFETs Q_1 and Q_2 (see **Lab5**), while R_L and R_C are the inductor and capacitor resistances. The theoretical value of ripple current $\Delta i_{L,pp}$ given by Equations 1-1 can be used in Equations 1-3 to estimate power losses. The resulting efficiency η of the buck regulator is given by Equation 1-4:

Equations 1-4
$$\eta = \frac{P_{out}}{P_{out} + P_{loss}}; \qquad P_{out} = \frac{V_{out}^2}{R_o} \qquad P_{loss} = P_{Q1} + P_{Q2} + P_L + P_C$$

The values of $\Delta i_{L,pp}$ and $\Delta v_{out,pp}$ including the effects of losses are given by:

Equation 1-5
$$\Delta i_{L,pp} \cong \frac{V_{out}(V_{in} - V_{out} - (R_{ds(on)}^{Q1} + R_L) I_{out})}{\eta V_{in} f_s L}$$

1-4 Ripple voltage of ceramic and electrolytic capacitors.

Given the inductor ripple current, the output ripple voltage is determined by the characteristics of the capacitor. Figure 1-3 shows the typical waveforms of ripple voltage generated by ceramic and electrolytic capacitors, the two types of capacitors majorly used in switching regulators applications.

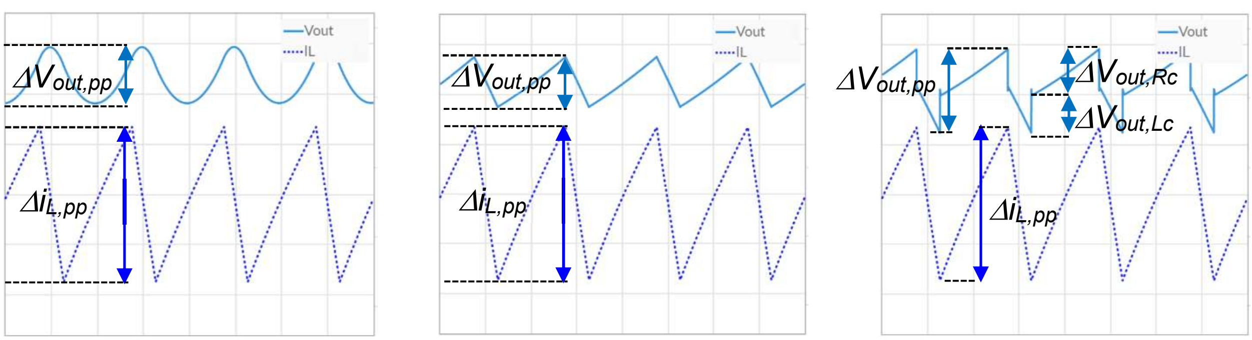

Figure 1-3. Output Ripple Voltage Waveforms for (a) Ceramic Capacitor, (b) Electrolytic Capacitor, (c) Electrolytic Capacitor with Effect of Parasitic Inductance.

The ripple voltage of ceramic capacitors is mainly determined by their capacitance (Figure 1-3(a)). The ripple voltage of electrolytic capacitors is mainly determined by their resistance (Figure 1-3(b)), and is influenced by their parasitic inductance L_C, which generates an additional square-wave ripple $\Delta V_{out,Lc}$ (Figure 1-3(c)). The simplified Equations 1-6 can be used to calculate the amplitude of peak-peak ripple voltage of ceramic and electrolytic capacitors:

Equations 1-6
$$\Delta V_{out,pp} \cong \begin{cases} \dfrac{\Delta i_{L,pp}}{8 f_s C} & \textit{ceramic capacitors} \quad \left(R_C = \dfrac{1}{2\pi f_s C}\right) \\ \Delta V_{out,Rc} + \Delta V_{out,Lc} = R_c \Delta i_{L,pp} + \dfrac{L_c}{L} V_{in} & \textit{electrolytic capacitors} \quad \left(R_C \; ? \; \dfrac{1}{2\pi f_s C}\right) \end{cases}$$

A more general formula of output ripple voltage can be derived for other types of capacitors having a resistance R_C comparable to the reactance $1/(2\pi f_s C)$.

1-5 MOSFETs switching losses.

The MOSFETs Q_1 and Q_2 of the half-bridge generate *switching losses* during their on-off and off-on commutations, given by Equation 1-7:

Equations 1-7
$$P_{Q1,sw} \cong \begin{cases} \frac{1}{2}(V_{in} + V_F) f_s (I_{vl} t_{sw,on} + I_{pk} t_{sw,off}) & I_{vl} > 0 \\ \frac{1}{2}(V_{in} + V_F) f_s I_{pk} t_{sw,off} & I_{vl} \le 0 \end{cases} \qquad P_{Q2,sw} \cong \begin{cases} 0 & I_{vl} \ge 0 \\ \frac{1}{2}(V_{in} + V_F) f_s |I_{vl}| t_{sw,off} & I_{vl} < 0 \end{cases}$$

where $I_{vl} = I_L - \Delta i_{L,pp}/2$ and $I_{vl} = I_L + \Delta i_{L,pp}/2$, V_F is the forward voltage of MOSFETs body diodes, $t_{sw,on}$ and $t_{sw,off}$ are the times the MOSFET needs to turn on and turn off, respectively,. The MOSFET $t_{sw,on}$ and $t_{sw,off}$ times depend on MOSFET parasitic capacitances, gate-to-source voltage threshold V_{th}, transconductance coefficient β (see **Lab1**) and gate driver voltage V_{dr}. The switching losses $P_{Q1,sw}$ can be added to the losses in Equation 1-5 to obtain a more accurate estimation of efficiency. The switching losses are important if the MOSFETs $t_{sw,on}$ and $t_{sw,off}$ switching times are long (this happens in MOSFETs with current ratings in the range of tens of Ampère, which are characterized by big parasitic capacitances) and if the switching frequency is high (this happens in buck regulators operating in the range of tens to hundreds milli Ampère, where the switching frequency can be high in the MHz range).

1-6 Inductor core losses.

Inductors are composed of a copper wire coil wounded around a magnetic core. The copper coil determines the resistance R_L of the inductor, which causes ohmic losses. The magnetic core also generates power loss, which is modeled by the Steinmetz Equation 1-8:

Equation 1-8
$$P_{L,core} \cong K_{fe} f_s^x \Delta i_{L,pp}^y$$

where the parameters K_{fe}, x and y depend on the material, shape and size of the magnetic core. The inductor core loss can influence the converter efficiency for high switching frequency and high ripple operating conditions.

Check Your Understanding

Note: The following questions are meant to help you self-assess your understanding so far. You can view the answer key for all "Check your Understanding" questions at the end of the lab.

1-1 What parameter determines the inductor ripple current in the buck regulator?

A. the capacitance
B. the inductance
C. the average output current

1-2 What parameter determines the output ripple voltage in the buck regulator?

A. the average output voltage
B. the inductance
C. the capacitance

1-3 What is the effect on the inductor ripple current and output ripple voltage in the buck regulator determined by an increase of the switching frequency?

A. both ripples increase
B. both ripples decrease
C. the inductor ripple current increases and the output capacitor voltage decreases

1-4 What is the effect of a higher inductor resistance on the buck converter efficiency?

A. the efficiency increases
B. the efficiency decreases
C. there is no effect

1-5 Does the resistance of the capacitor influence the amplitude of the inductor ripple current?

A. yes
B. it depends on the average output voltage
C. no

1-6 What parameter does majorly influence the amplitude of output voltage ripple if an electrolytic capacitor is used?

A. the switching frequency
B. the resistance of the capacitor
C. the load current

2 Exercise

TI's CSD15380F3 (http://www.ti.com/lit/ds/symlink/csd15380f3.pdf) MOSFET is used for Q_1 and Q_2 in the **Discrete Buck Section** of the TI Power Electronics Board for NI ELVIS III. The MOSFET has the following nominal parameters: V_{th} = 1.1V, β = 0.24A/V^2, λ = 0.02V^{-1}. The MOSFET is also characterized by the following parameters under the operating conditions determined by the setup of the **Discrete Buck Section** of the TI Power Electronics Board for NI ELVIS III: $R_{ds(on)}$ = 1.2Ω, $t_{sw,on} \cong$ 0.2ns, $t_{sw,off}$ =0.3ns. The inductor can be set with the following two options: (a) L=15μH, R_L=140mΩ, (b) L=48μH, R_L=400mΩ, and the capacitor can be set with the following two options: (a) C=100μF, R_c=55mΩ, (b) C=10μF, R_c=5mΩ.

2-1 Assuming V_{in}= 7V, V_{out}= 5.0V, f_s = 200kHz, and selecting option (b) for the inductor setup and option (b) for the capacitor setup, use the equations provided in the **Theory and Background** section to calculate:

- the average inductor ripple current, in milli Ampère with one decimal digit: I_L = ____________
- the peak-peak amplitude of the ideal inductor ripple current, in milli Ampère with one decimal digit: $\Delta i_{L,pp(ideal)}$ = ____________
- the peak-peak amplitude of the ideal output ripple voltage, in milli Volt with one decimal digit: $\Delta v_{o,pp(ideal)}$ = ____________

2-2 Using the results of ripple calculations from 2-1 and equations provided in the **Theory and Background** section, calculate the power loss of MOSFETs Q_1 and Q_2, inductor and capacitor, in milli Watt with three decimal digits, and report the results in Table 2-1:

Table 1-1 Power losses of MOSFETs, inductor and capacitor of Buck Regulator in DC Operation.

	MOSFET Q_1 ohmic loss	MOSFET Q_1 switching loss	MOSFET Q_2 ohmic loss	MOSFET Q_2 switching loss	inductor ohmic loss	capacitor ohmic loss
loss [mW]						

2-3 Using the results obtained from previous point 2-1, and the equations provided in the **Theory and Background** section, calculate the efficiency $\eta = P_{out} / (P_{out}+P_{loss})$, with three decimal digits, the peak-peak inductor ripple current and the average input current $I_{in} = P_{in}/V_{in} = (P_{out}+P_{loss}) / V_{in}$, in milli Ampère with one decimal digit:

η = ____________ $\Delta i_{L,pp(real)}$ = ____________

I_{in} = ____________

3 Simulate

The goal of the simulations in this section is to analyze the operation of the L-C filter of a Buck Regulator under DC open loop conditions. You will verify the consistency of the perk-peak amplitude of inductor ripple current and output ripple voltage and of efficiency calculated in the **Exercise** Section. You will also observe the inductor current and output voltage waveforms under different operating conditions.

3-1 Instructions

1. Open *Lab6 – Buck Regulator L-C Filter Operation* from this file path: https://www.multisim.com/content/bdUiT8S52XAVbZkFwhgY44/lab-6-buck-regulator-l-c-filter-operation/. The circuit schematic for the analysis of the Buck Regulator L-C filter operation is shown in Figure 3-1.

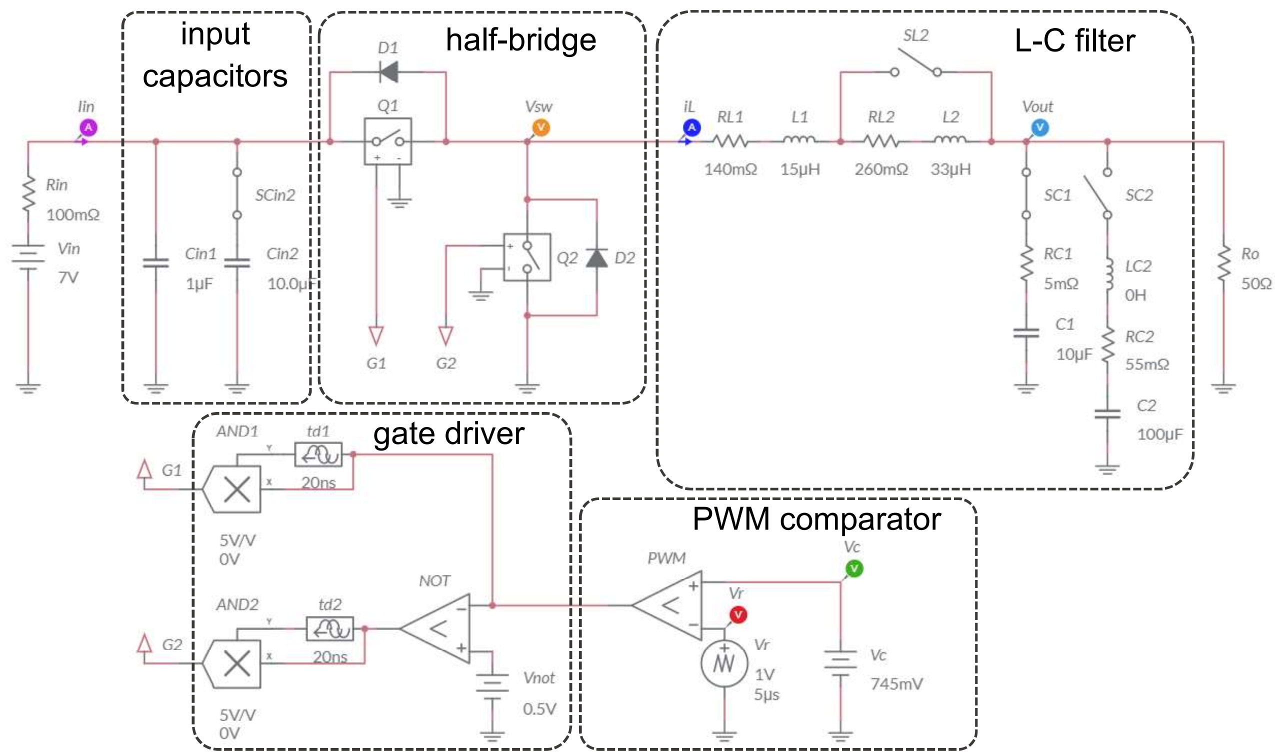

Figure 3-1. Multisim Live Circuit Schematic for the Analysis of Buck Regulator L-C Filter.

The L-C filter is configurable by means of switches SL1, SC1 and SC2 as follows:

- SL2 closed: $L = L_1 = 15\mu H$, $R_L = R_{L1} = 140m\Omega$;
- SL2 open: $L = L_1+L_2 = 48\mu H$, $R_L = R_{L1}+R_{L2} = 400m\Omega$;
- SC1 closed, SC2 open: $C = C_1 = 10\mu F$, $R_c = R_{C1} = 5m\Omega$;
- SC2 closed, SC1 open: $C = C_2 = 100\mu F$, $R_c = R_{C2} = 55m\Omega$.

[**Notes: 1)** the input capacitors C_{in1} and C_{in2} are normally included in buck regulators to obtain an input current I_{in} with a small amplitude ripple; **2)** the model of capacitor C_2 includes a parasitic inductance L_{C2} initially set at 0H].

2. Set SL2 to be OPEN, SC1 to be CLOSED, SC2 to be OPEN and SCin2 to be CLOSED.
3. Select *Interactive* simulation and *Split* visualization options.
4. Check the *Periodic* option box for voltage probe V_{out} and current probes i_L and I_{in} in *Measurement labels* menu.
5. Set the simulation circuit parameters as follows:
   - V_{in}: *DC_mag* = 7.0V;
   - V_r: *VA* = 1V, *Per* = 5μs, *TF* = 2.5μs, Offset 0V;
   - R_o: 50Ω;
   - V_c: *DC_mag* = 745mV
6. Run the simulation and wait until it ends.
7. Read the average value V_{AV} displayed by the output voltage probe V_{out}, in Volt with four decimal digits, and report the result in Table 3-1.
8. Read the peak-peak value V_{pp} displayed by the output voltage probe V_{out}, in milli Volt with one decimal digit, and report the result in Table 3-1.
9. Read the average value I_{AV} displayed by the inductor current probe i_L, in milli Ampère with one decimal digit, and report the result in Table 3-1.
10. Read the peak-peak value I_{pp} displayed by the inductor current probe i_L, in milli Ampère with one decimal digit, and report the result in Table 3-1.
11. Read the average value I_{AV} displayed by the input current probe I_{in}, in milli Ampère with one decimal digit, and report the result in Table 3-1.
12. Calculate the efficiency $\eta = (V_{out}I_{out}) / (V_{in}I_{in})$, with three decimal digits, and report the result in Table 3-1.
13. Import in Table 3-1 the values of V_{out}, $\Delta V_{out,pp}$, I_{out}, $\Delta i_{L,pp}$, I_{in} and η obtained in the **Exercise** calculations

Table 3-1 L-C filter operation and converter efficiency with L = 48μH, R_L = 400mΩ; C = 10μF, R_c = 5mΩ.

	V_{out} [V]	$\Delta V_{out,pp}$ [mV]	$I_L = I_{out}$ [mA]	$\Delta i_{L,pp}$ [mA]	I_{in} [mA]	η
from simulations						
from calculations						

14. Enter the simulation results from Table 3-1 in the first row of Table 3-2.
15. Re-run the simulation using the switch setups listed in Table 3-2, and report the resulting values of V_{out}, $\Delta V_{out,pp}$, I_{out}, $\Delta i_{L,pp,}$, I_{in} and η.

Table 3-2 L-C filter operation and converter efficiency under different filter setup.

	SL2	SC1	SC2	V_{out}	$\Delta V_{out,pp}$	$I_L = I_{out}$	$\Delta i_{L,pp}$	I_{in}	η

				[V]	[mV]	[mA]	[mA]	[mA]	
(a)	open	closed	open						
(b)	closed	closed	open						
(c)	open	open	closed						
(d)	closed	open	closed						

3-1 Do the simulations match the calculations in Table 3-1?

A. yes
B. no
Please provide your comments: ____

____

3-2 Is the peak-peak amplitude of the output ripple voltage small compared to the average output voltage?

A. yes
B. no
why? ____

____

3-3 What switch setup determines the smallest peak-peak amplitude of inductor ripple current in Table 3-2?

(a) ☐
(b) ☐
(c) ☐
(d) ☐
why? ____

____

3-3 What switch setup determines the biggest peak-peak amplitude of output ripple voltage in Table 3-2?

(a) ☐
(b) ☐
(c) ☐

(d) ☐

why? ____

____

Troubleshooting tips:

- If the simulation does not converge and you get some error message, reload *Lab6 – Buck Regulator L-C Filter Operation* from this file path `https://www.multisim.com/content/sRY9ZW7saFpr4MKWu2a5A5/lab-5-buck-regulator-half-bridge-pwm-operation/` and restart the simulation following the instructions.

4 Implement

The experiments in this section allow you to observe the behavior of the L-C filter of a buck regulator in steady-state operation. You will measure the peak-peak amplitudes of inductor ripple current and output ripple voltage, under different conditions. Then, you will use the measurements to estimate the inductance of the inductor, and the capacitance, the resistance and the parasitic inductance of capacitors. Finally, you will measure the efficiency of the buck regulator. The **Discrete Buck Section** of the TI Power Electronics Board for NI ELVIS III shown in Figure 4-1 will be used to perform the experiments. [**Note:** The max input voltage V_{in} is 12V]. A 50Ω resistance R_o can be connected to the output of the L-C filter by means of the Jumper J16. The TI's CSD15380F3 half-bridge MOSFETs are characterized by a typical 1.2Ω on-state resistance at 4.5V gate-to-source voltage. The PWM modulator uses a TI's TLV7011DPWR comparator, and the half-bridge MOSFET gate driver is a TI's TPS51601ADRBR. The links to the datasheets are available below:

- CSD15380F3 MOSFET: (http://www.ti.com/lit/ds/symlink/csd15380f3.pdf)
- TLV7011DPWR COMPARATOR: (http://www.ti.com/lit/ds/symlink/tlv7011.pdf)
- TPS51601ADRBR GATE DRIVER: (http://www.ti.com/lit/ds/symlink/tps51601a.pdf).

The L-C filter is configurable by means of jumpers J39 and J12 as follows:

- J39 closed: L = 15µH, R_L = 140mΩ;
- J39 open: L = 48µH, R_L = 400mΩ;
- J12 shorting TP161-TP159: C = 10µF, R_c = 5mΩ (ceramic capacitor);
- J12 shorting TP161-TP160: C = 100µF, R_c = 55mΩ (electrolytic capacitor).

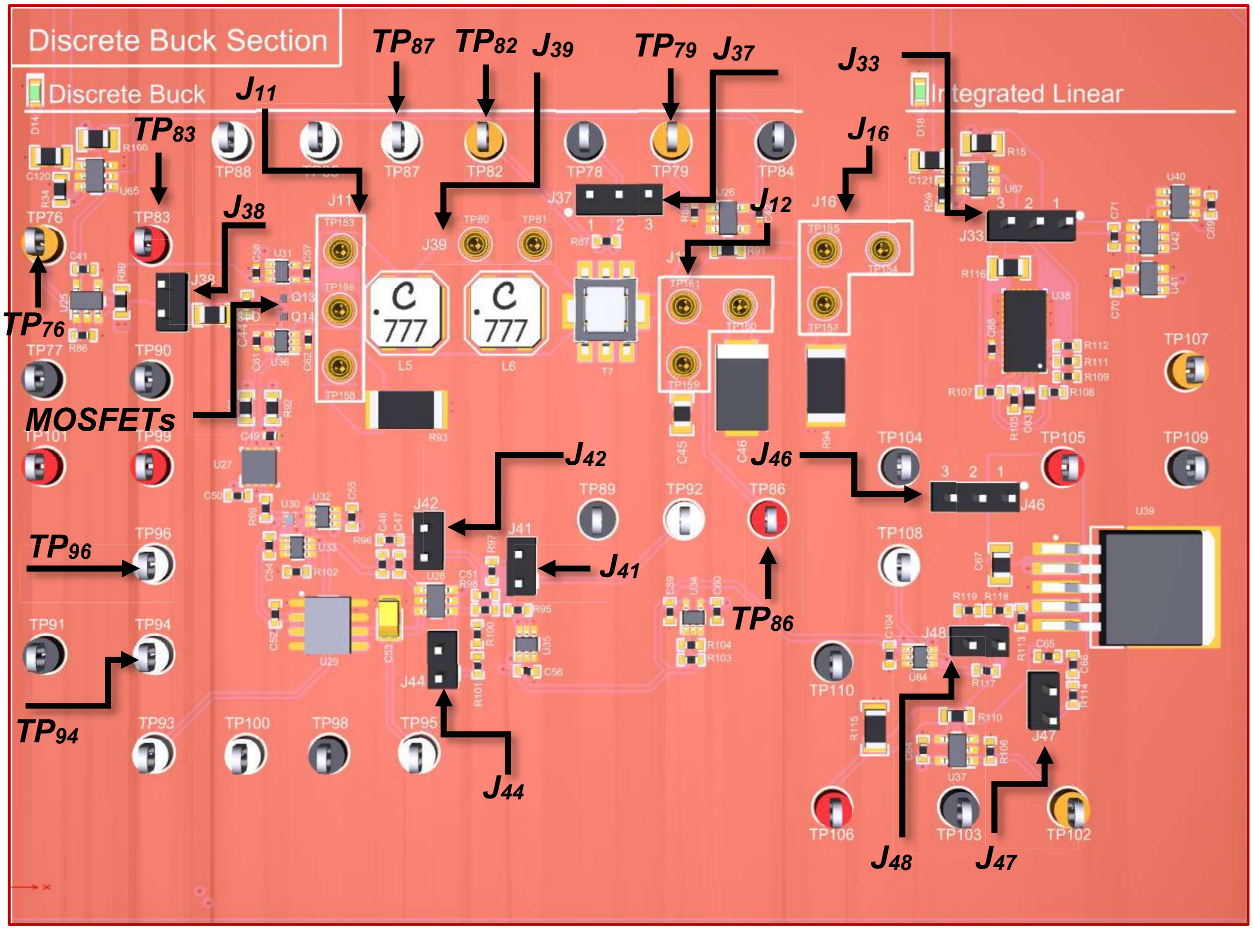

Figure 4-1. TI Power Electronics Board for NI ELVIS III - Discrete Buck Section Used for the Analysis of Buck Regulator L-C Filter Operation.

The board uses a current sensing transformer and a resistor (T7 and R87 shown in Figure 4-1) to sense the inductor ripple current. The transformer generates a voltage test point TP82, that can be measured by means of a voltage probe. As the voltage-to-current transconductance of the sensing transformer is 0.5, dividing the voltage measured at test point TP82 by 2 provides the peak-peak amplitude of the inductor ripple current $\Delta i_{L,pp}$. [**Note:** the parameters provided in the following instructions for instruments setup may require some adjustment due to thermal effects and tolerances of TI Power Electronics Board components]

4-1 General Instructions

1. Open *Power Supply*, *Function Generator*, *Oscilloscope* and *Digital Multimeter* using Measurements Live. For help on launching instruments, refer to this help document: http://www.ni.com/documentation/en/ni-elvis-iii/latest/getting-started/launching-soft-front-panels/
2. Open the *User Manual* of TI Power Electronics Board for NI ELVIS III from this file path: http://www.ni.com/en-us/support/model.ti-power-electronics-board-for-ni-elvis-iii.html

3. Read the *User Manual* sections *Description*, *Warnings* and *Recommendations* regarding *Discrete Buck Section*.
4. Open the *TI Top Board RT Configuration Utility* of TI Power Electronics Board for NI ELVIS III (See Required Tools and Technology section for download instructions), and select *Lab6 – Buck Regulator L-C Filter Operation*.

4-2Experiment 1 Instructions

1. Configure the jumpers of the board as indicated in Table 4-2-1.
2. Connect and configure the instruments as indicated in Tables 4-2-2 and 4-2-3.

Table 4-2-1 Jumpers setup

J11	J12	J16	J33	J37	J38
short TP156-TP153	short TP160-TP161	short TP155-TP157	short 2-3	short 1-2	short

J39	J41	J42	J44	J46	J47	J48
open	short	short	short	short 2-3	short	open

Table 4-2-2 Instruments Connections

Power Supply	connect to red and black banana connectors
Oscilloscope	connect CH-1 to TP83 (V_{in}), connect CH-2 to TP86 (V_{out}) connect CH-3 to TP87 (V_{sw}), connect CH-4 to TP82 (I_L)
Function Generator	connect CH-1 to FGEN1 BNC connector (→TP94 = PWM comparator V_r) connect CH-2 to FGEN2 BNC connector (→TP96 = PWM comparator V_c)
Digital Multimeter	connect Voltage input to TP86 (V_{out}), TP82 (I_L) or TP76 (I_{in}), as per instructions

Table 4-2-3 Recommended Instruments Configuration and setup

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive			
Oscilloscope	*Trigger*: Analog Edge, CH-3, set to 50%	*Horizontal*: 2us/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 1V/div • offset -4V	*Channel 2*: ON • DC coupling • 10mV/div • offset -5.0V	*Channel 3*: ON • DC coupling • 1V/div • offset -4V	*Channel 4*: ON • DC coupling • 100mV/div offset 0V
Function Generator	*Channel 1*: Triangle, Frequency 200kHz, Amplitude 1Vpp, DC offset 0.5V *Channel 2*: Sine, Frequency 1Hz, Amplitude 0Vpp, DC offset 855mV			
Digital Multimeter	*Measurement mode*: DC voltage; *Range*: Automatic			

3. Using the *Oscilloscope* cursors in *Manual Mode*:
   - measure the peak-peak amplitude of the output ripple voltage $\Delta v_{out,pp}$ on CH-2, in milli Volt with one decimal digit of accuracy, and report the result in Table 4-2-4 [**Notes: 1)** if the ripple voltage waveform is as shown in Figure 1-3(c), measure the amplitude of the steep front $\Delta v_{out,Lc}$ and the amplitude of the rising ramp

portion $\Delta v_{out,Rc}$ separately; **2)** neglect the high-frequency noise, and measure the peak-peak amplitude of the ripple voltage waveforms as shown in Figure 1-3];

- measure the peak-peak amplitude of the inductor ripple current $\Delta i_{L,pp}$ on CH-4, in milli Ampère with one decimal digit of accuracy, and report the result in Table 4-2-4.

4. Connect *Digital Multimeter* to TP79, measure the average output current I_{out}, in milli Ampère with one decimal digit of accuracy, and report the result in Table 4-2-4;
5. Connect *Digital Multimeter* to TP76, measure the average input current I_{in}, in milli Ampère with one decimal digit of accuracy, and report the result in Table 4-2-4;
6. Calculate the efficiency $\eta = (V_{out}I_{out})/(V_{in}I_{in})$, with three decimal digits, and report the result in Table 4-2-4.
7. Calculate the inductance of the inductor $L=V_{out}(V_{in}-V_{out}-(R_{dson}+R_L)I_{out})/(\eta V_{in}f_s\Delta i_{L,pp})$, in micro Henry with three decimal digits, and report the result in Table 4-2-4;
8. If the ripple voltage waveform looks like in Figure 1-3(a), calculate the capacitance of the capacitor $C=\Delta i_{L,pp}/(8f_s\Delta v_{out,pp})$, in micro Farad with three decimal digits, and report the result in Table 4-2-4.
9. If the ripple voltage waveform looks like in Figure 1-3(b), calculate the resistance of the capacitor $R_C=\Delta V_{out,pp}/\Delta i_{L,pp}$, in milli Ohm with no decimal digits, and report the result in Table 4-2-4.
10. If the ripple voltage waveform looks like in Figure 1-3(c), calculate the parasitic inductance of the capacitor $L_C=L\Delta V_{out,Lc}/V_{in}$, in nano Henry with no decimal digits, and the resistance of the capacitor $R_C=\Delta V_{out,Rc}/\Delta i_{L,pp}$, in milli Ohm with no decimal digits, where L is the inductance of the inductor from step 7, and report the results in Table 4-2-4.
11. Stop *Power Supply*, *Function Generator*, *Digital Multimeter* and *Oscilloscope*.
12. Repeat the steps 3-14 for all the jumpers setups listed in Table 4-2-4.

Table 4-2-4 L-C filter operation and converter efficiency under different filter setup.

	J12	J39	η	$\Delta i_{L,pp}$ [mA]	$\Delta V_{out,pp}$ [mV]	$\Delta V_{out,Lc}$ [mV]	$\Delta V_{out,Rc}$ [mV]	L [µH]	C [µF]	R_c [mΩ]	L_c [nH]
(a)	short TP159-TP161	open									
(b)	short TP159-TP161	closed									
(c)	short TP160-TP161	open									
(d)	short TP160-TP161	closed									

4-2-1 Are the values of inductance *L* of the inductor determined from experimental measurements close to the nominal values?

A. yes
B. no
C. other: ______________________________

Please provide your comments: ______________________________

____

4-2-2 Is the shape of the output ripple voltage the same for the two capacitors?

A. yes
B. no
C. other: ______________________________

Please provide your comments: ______________________________

____

4-2-3 Given an inductor setup, what is the capacitor determining the biggest peak-peak amplitude of the output ripple voltage?

A. the 10µF capacitor
B. the 100µF capacitor
C. other: ______________________________

Please provide your comments: ______________________________

____

4-2-4 For what capacitor did you observe the shape of the output ripple voltage waveform showing the effect of parasitic inductance?

A. the 10μF capacitor
B. the 100μF capacitor
C. other: ____

Please provide your comments: ________________________________

____

4-2-5 Does the parasitic inductance of the capacitor change with the setup of the main inductor?

A. yes
B. no
C. other: ____

Please provide your comments: ________________________________

____

4-3 Experiment 2 Instructions

1. Configure the jumpers of the board as indicated in Table 4-3-1.

Table 4-3-1 Jumpers setup

J11	J12	J16	J33	J37	J38
short TP156-TP153	short TP159-TP161	short TP155-TP157	short 2-3	short 1-2	short

J39	J41	J42	J44	J46	J47	J48
short	short	short	short	short 2-3	short	open

2. Connect and configure the instruments as indicated in Tables 4-3-2 and 4-3-3.

Table 4-3-2 Instruments Connections

Power Supply	connect to red and black banana connectors
Oscilloscope	connect CH-1 to TP83 (V_{in}), connect CH-2 to TP86 (V_{out}) connect CH-3 to TP87 (V_{sw}), connect CH-4 to TP79 (I_L)
Function Generator	connect CH-1 to FGEN1 BNC connector (→TP94 = PWM comparator V_r) connect CH-2 to FGEN2 BNC connector (→TP96 = PWM comparator V_c)
Digital Multimeter	connect Voltage input to TP86 (V_{out})

Table 4-3-3 Instruments Configuration and setup

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive

Oscilloscope	*Trigger*: Analog Edge, CH-3, set to 50%	*Horizontal*: 2us/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 1V/div • offset -4V	*Channel 2*: ON • DC coupling • 1V/div • offset -4V	*Channel 3*: ON • DC coupling • 1V/div • offset -4V	*Channel 4*: ON • DC coupling • 500mV/div offset 0V
Function Generator	*Channel 1*: Triangle, Frequency 200kHz, Amplitude 6.0Vpp, DC offset 3.0V *Channel 2*: Sine, Frequency 1Hz, Amplitude 0Vpp, DC offset 1.0V			
Digital Multimeter	*Measurement mode*: DC voltage; *Range*: Automatic			

3. Set the *Function Generator* CH-2 DC offset to 1.0V (PWM control voltage V_c).
4. Run *Oscilloscope*, *Digital Multimeter*, *Function Generator* and *Power Supply*.
5. Read the *Digital Multimeter* measurement of output voltage V_{out}, in Volt with three decimal digit of accuracy, and report the result in Table 4-3-4.
6. Repeat step5, setting the *Function Generator* CH-2 DC offset to the values of the PWM control voltage V_c listed in Table Table 4-3-4, and report the results in Table 4-3-4.
7. Stop *Power Supply*, *Function Generator*, *Digital Multimeter* and *Oscilloscope*.
8. Using the equations provided in **Theory and Background** Section, calculate the duty-cycle D, with tree decimal digits of accuracy, the theoretical output voltage V_{out}, in Volt with three decimal digits of accuracy, for each value of the PWM control voltage V_c, and report the results in Table 4-3-4.

Table 4-3-4 Output Voltage of Buck Regulator under Different Duty-Cycle Conditions.

V_c [V]	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
D									
V_{out} [V] (measured)									
V_{out} [V] (calculated)									

4-3-1 Are the measurements and calculations trends consistent?

A. yes
B. no
C. other: ____

Please provide your comments: ________________________________

____

4-3-2 Are the measured values of average output voltage greater or lower than the calculated values?

A. greater

B. lower

C. other: ____

Please provide your comments: ________________________________

____

Troubleshooting tips:

- If the regulator does not work, verify the correct setup and connections of jumpers and instruments, following the directions provided in Tables 4-1, 4-2 and 4-3, and restart the experiment.

5 Analyze

5-1 Using the results collected in Table 4-2-4, analyze the values of efficiency versus peak-peak amplitude of inductor ripple current, and discuss the correlation among these values based on ***Theory and Background*** equations:

____

____

____

5-2 Using the results collected in Table 4-3-4, graph the values of voltage conversion ratio $M = V_{out}/V_{in}$, as function of the duty-cycle D, comparing measurements and calculations:

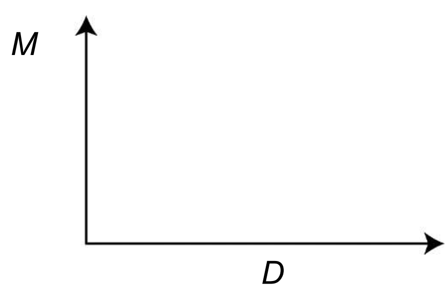

Figure 5-1 Voltage Conversion Ratio of Buck Regulator as Function of Duty-Cycle.

5-3 Discuss the differences between calculated and measured data, based on ***Theory and Background*** equations:

____

____

6 Conclusion

6-1 Summary

Write a summary of what you observed and learned about the buck regulator L-C filter operation, discussing the impact of the inductor an capacitor parameters on the peak-peak amplitude of inductor ripple current and output ripple voltage, and on the buck regulator efficiency.

6-2 Expansion Activities

6-2-1. Investigate the influence of switching frequency on L-C filter operation, by means of TI Power Electronics Board for NI ELVIS III of Figure 4-1.

a. Use the same connections and configurations indicated in Tables 4-1 and 4-2.
b. Use the jumpers configuration adopted for test (d) of Table 4-4.
c. Set the Frequency of *Function Generator* CH-1 at 250kHz.
d. Run *Oscilloscope*, *Function Generator* and *Power Supply*.
e. Using the *Oscilloscope* cursors in *Manual Mode*:

- measure the peak-peak amplitude of the inductor ripple current $\Delta i_{L,pp}$ on CH-4, in milli Ampère with one decimal digit of accuracy, and report the result in Table 6-1;
- measure the peak-peak amplitude of the output ripple voltage $\Delta v_{out,pp}$ on CH-2, in milli Volt with one decimal digit of accuracy, and report the result in Table 6-1.

f. Repeat step e. for all the values of the Frequency of *Function Generator* CH-1 listed in Table 6-1.
g. Stop *Power Supply*, *Function Generator* and *Oscilloscope*.

Table 6-1 Peak-peak amplitude of inductor ripple current and output ripple voltage versus the switching frequency

f [kHz]	250	300	350	400	450	500
$\Delta i_{L,pp}$ [mA]						
$\Delta v_{out,pp}$ [mV]						

6-1 Analyze the values of peak-peak amplitude of inductor ripple current and output ripple voltage as the switching frequency increases and discuss them based on ***Theory and Background*** equations:

____

____

____

6-2-2. Investigate the influence of input voltage on L-C filter operation, by means of TI Power Electronics Board for NI ELVIS III of Figure 4-1.

a. Use the same connections and configurations indicated in Tables 4-2-1 and 4-2-2.
b. Use the jumpers configuration adopted for test (c) of Table 4-2-4.
c. Set the voltage of *Power Supply* at 6.0V.
d. Run *Oscilloscope*, *Function Generator* and *Power Supply*.
e. Using the *Oscilloscope* cursors in *Manual Mode*:

- measure the peak-peak amplitude of the inductor ripple current $\Delta i_{L,pp}$ on CH-4, in milli Ampère with one decimal digit of accuracy, and report the result in Table 6-2;
- measure the peak-peak amplitude of the output ripple voltage $\Delta v_{out,pp}$ on CH-2, in milli Volt with one decimal digit of accuracy, and report the result in Table 6-2.

f. Repeat step e. for all the values of the *Power Supply* voltage listed in Table 6-2.
g. Stop *Power Supply*, *Function Generator* and *Oscilloscope*.

Table 6-2 Peak-peak amplitude of inductor ripple current and output ripple voltage versus the input voltage

V_{in} [V]	6.0	6.5	7.0	7.5	8.0	8.5
$\Delta i_{L,pp}$ [mA]						
$\Delta v_{out,pp}$ [mV]						

6-2 Analyze the values of peak-peak amplitude of inductor ripple current and output ripple voltage as the input voltage increases and discuss them based on ***Theory and Background*** equations:

____

____

____

6-2-3. Verify the influence of parasitic inductance on the output ripple voltage waveform and peak-peak amplitude, using the Multisim Simulation Schematic of Figure 3-1.

a. Follow the simulation instructions provided in Section 3-1.
b. Before running the simulation, set the switches SL2, SC1 and SC2 corresponding to filter configuration (c) or (d) of Table 4-4, and set the value of the inductance LC2 in series to the capacitor C2 equal to the corresponding value L_c recorded in Table 4-4.
c. Run the simulation, and measure the peak-peak amplitude or output ripple voltage using the *Grapher* cursor on the output voltage trace
d. Compare the result with the corresponding measured value recorded in Table 4-4.

6-3 Resources for learning more

- This book provides the fundamentals of switching regulators:
  S. Maniktala, *Switching Power Supplies A - Z*, Newness