ECEN 438/738 – Power Electronics Spring 2025

Lab 7: Buck Converter: Closed Loop

Lab 7: Buck Regulator: Closed Loop

The goal of this lab is to analyze the closed loop operation of a buck regulator. We investigate the impact of the error amplifier on the output voltage DC regulation, and on the capability of rejecting output voltage AC perturbations caused by load current noise, which is one of the most important features of buck regulators. First, we will review the simplified DC and AC model of a closed loop buck regulator. Next, we will predict its Dc accuracy and AC response to load perturbations. Then, we will simulate the buck regulator in DC and AC operation to verify the DC regulation capability. Finally, we will perform experiments to observe the response of a real buck regulator to AC load perturbations, and will compare the results of calculations, simulations and measurements to verify their consistency.

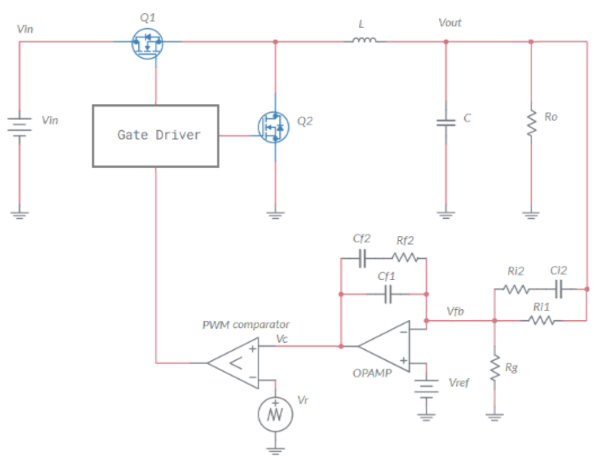

Figure 1-1. Closed Loop Buck Regulator.

Learning Objectives

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

1. Given a buck regulator and the characteristics of its L-C filter and error amplifier, you will calculate the DC operating point and the AC response to load perturbations, with specified units and accuracy, by applying the appropriate theoretical formulae.
2. Given a buck regulator and the characteristics of its L-C filter and error amplifier, you will simulate its DC operation for different source voltage values, to determine the accuracy of theoretical model predictions, with specified units and accuracy, by comparing the appropriate sets of data and results
3. Given a real buck regulator, a power supply and a dynamic load, you will measure the accuracy of the DC output voltage with respect to the desired nominal value, and the amplitude of output voltage AC perturbations caused by AC load current perturbations, 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 means of Multisim Live
- ✓ Results of experiments performed by means of TI Power Electronics Board for NI ELVIS III
- ✓ Observations on simulations and experiments
- ✓ Answers to questions

Your instructor may expect you 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 basic concepts and equations of a buck regulator in closed loop operation (see the reference given in section 6-3 to learn more). We discuss the impact of the L-C filter and of the error amplifier on DC offset error and the capability of the buck regulator to attenuate the effects of AC load current perturbations.

1-2 Feedback Action of the Error Amplifier.

Figure 1-2 shows a buck regulator in closed loop operation. The error amplifier consists of the OPAMP, the voltage reference V_{ref}, the capacitors $\{C_{f1}, C_{f2}, C_{i2}\}$, and the resistors $\{R_g, R_{i1}, R_{i2}, R_{f2}\}$. The error amplifier compares the output voltage V_{out} to the desired DC nominal value $V_{outDC,nom}$, and generates the PWM control signal V_c ensuring that $V_{out} = V_{outDC,nom}$. Thanks to the error amplifier, the buck regulator generates a well regulated output voltage, rejecting the effects of load changes, which is one of the most important feature of buck regulators. The components $\{C_{f1}, C_{f2}, C_{i2}\}$ and $\{R_g, R_{i1}, R_{i2}, R_{f2}\}$ set the poles and zeros of the error amplifier, and determine its sensitivity to output voltage changes (See **Lab 3** for error amplifier operation).

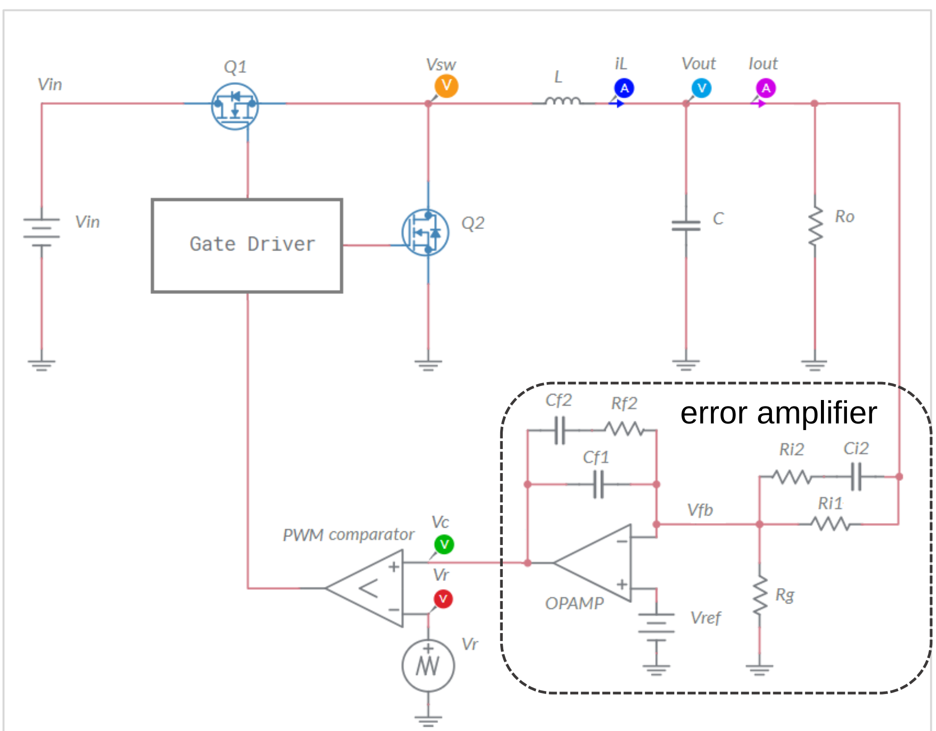

Figure 1-2. Buck Regulator in Closed Loop Operation.

1-3 Closed Loop DC Analysis of the Buck Regulator

The DC output voltage V_{outDC} of a buck regulator is determined by the DC source voltage V_{inDC} and by the DC PWM control voltage V_{cDC}. For a buck regulator with efficiency η, it is:

Equation 1-3-1

$$V_{outDC} = \frac{D}{\eta} V_{in} = \frac{V_{cDC}}{\eta V_{rpp}} V_{inDC}$$

where D is the duty-cycle of the MOSFET half-bridge, and V_{rpp} is the peak-peak amplitude of the triangular carrier signal of the PWM comparator (see **Lab5**). The error amplifier determines the DC PWM control voltage V_{cDC}, given by Equation 1-3-2:

Equation 1-3-2

$$V_{cDC} = A_{dc}(V_{ref} - V_{outDC} H)$$

where A_{dc} is the error amplifier DC gain and $H=(1+R_{i1}/R_g)^{-1}$ is the voltage sensor gain (see **Lab3**). Combining Equations 1-3-1 and 1-3-2 provides the buck regulator DC output voltage:

Equation 1-3-3

$$V_{outDC} = \frac{A_{dc} V_{ref} V_{in}}{\eta V_{rpp} + A_{dc} V_{in} H}$$

An unlimited DC gain $A_{dc} = \infty$ would determine an output voltage $V_{outDC,nom}$ equal to:

Equation 1-3-4

$$V_{outDC,nom} = \frac{V_{ref}}{H}$$

Based on Equations 1-3-3 and 1-3-4, the output voltage DC offset error of a buck regulator is given by Equation 1-3-5:

Equation 1-3-5

$$ERR_{DC} \cong \frac{A_{dc} V_{ref} V_{in}}{\eta V_{rpp} + A_{dc} V_{in} H} - \frac{V_{ref}}{H}$$

The tolerance of resistances R_{i1} and R_g and of the voltage reference V_{ref} influence the nominal value $V_{outDC,nom}$ given by Equation 1-3-4 and the DC offset error given by Equation 1-3-5. Typically, the accuracy of the voltage divider resistances and of the reference voltage is about 1% (See **Lab4** for effects of parameters tolerances on the DC operation of an error amplifier).

1-4 Open Loop Output Impedance of the Buck Regulator

AC load current perturbations are frequent in applications where loads are logic devices, like microprocessors. A load current AC perturbation $I_{outAC}sin(2\pi ft)$ causes an AC perturbation $V_{outAC}sin(2\pi ft+\theta)$ in the output voltage of the buck regulator. In open loop operation, the ratio $Z_{out,OL}$ between the amplitude of the output voltage V_{outAC} and load current AC perturbation I_{outAC} is defined as *open loop output impedance*, and is given by Equation 1-4-1:

Equation 1-4-1

$$\left.\frac{V_{outAC}}{I_{outAC}}\right|_{open\,loop} = Z_{out,OL} = R_{DC}\frac{N_L(f)N_C(f)}{M(f)}$$

$$N_L(f)=\sqrt{\left(1+\frac{f^2}{f_L^2}\right)};\;\; N_C(f)=\sqrt{\left(1+\frac{f^2}{f_C^2}\right)};\;\; M(f)=\sqrt{\left(1-\frac{f^2}{f_n^2}\right)^2+\frac{f^2}{Q^2 f_n^2}};$$

$$R_{DC}=R_L+DR_{ds(on)}^{Q1}+(1-D)R_{ds(on)}^{Q2};\;\; f_L=\frac{R_L}{2\pi L};\;\; f_C=\frac{1}{2\pi R_C C};\;\; f_n=\frac{1}{2\pi\sqrt{LC}};\;\; Q=R_o\sqrt{\frac{C}{L}}$$

where L and R_L are the inductance and resistance of the inductor, C and R_c are the capacitance and resistance of the capacitor, $R_{ds(on)}^{Q1}$ and $R_{ds(on)}^{Q2}$ are the on-state resistances of half-bridge MOSFETs, D is the duty-cycle, and R_o is the DC load resistance. Normally, $f_L < f_n < f_c$. From Equation 1-4-1 it follows that a low output impedance is a desirable feature of a buck regulator, as it involves a better rejection capability of AC load current perturbations. At high frequency, the output impedance is equal to the resistance of the capacitor, $Z_{out,OL} \cong R_C$. At low frequency, the output impedance is equal to the sum of inductor and MOSFETs resistance, $Z_{out,OL} \cong R_{DC}$.

1-5 Error Amplifier Gain

The buck regulator capability to reject the effects of AC load current perturbations improves in closed loop operation, thanks to the feedback action of the error amplifier. When the error amplifier senses an AC perturbation of amplitude V_{outAC} in the output voltage, it generates an AC signal of amplitude $V_{cAC} = G_{ea}V_{outAC}$, where G_{ea} is the *error amplifier gain*, given by Equation 1-5-1, for the error amplifier configuration of Figure 1-2:

Equation 1-5-1

$$G_{ea}(f)=\frac{V_{cAC}}{V_{outAC}}=\begin{cases}\dfrac{f_0}{f}\dfrac{1+f^2/f_Z^2}{1+f^2/f_P^2} & f>\dfrac{f_0}{A_{dc}}\\[2ex] A_{dc}H & f<\dfrac{f_0}{A_{dc}}\end{cases}$$

The frequencies f_0, f_P and f_Z are set by capacitances $\{C_{f1},C_{f2},C_{i2}\}$ and resistances $\{R_g,R_{i1},R_{i2},R_{f2}\}$, and determine the sensitivity of the error amplifier with respect to AC perturbations of the output voltage.

1-6 Control-to-Output Gain of the Buck Regulator

The AC perturbation V_{cAC} generated by the error amplifier determines an additional AC perturbation in the output voltage, whose magnitude is given by Equation 1-6-1:

Equation 1-6-1

$$\frac{V_{outAC}}{V_{cAC}} = G_c(f) = \frac{V_{inDC}}{V_{rpp}} \frac{N_c(f)}{M(f)}$$

where $N_c(f)$ and $M(f)$ are given in Equation 1-4-1. The function G_c is defined as *control-to-output gain* of the buck regulator. The AC perturbation generated by the error amplifier attenuates the effect of the perturbation caused by the AC load current perturbation.

1-7 Loop Gain of the Buck Regulator

The product $T = G_c G_{ea}$ is defined as *loop gain* of the buck regulator, expressing the closed loop sensitivity of buck regulator to AC perturbations. A high loop gain T involves a higher sensitivity to AC perturbations and a higher efficacy of the buck regulator in attenuating them (see also **Lab4** for loop gain). Equation 1-6-1 highlights that the control-to-output gain is equal to V_{inDC}/V_{rpp} at low frequency, while it decreases as frequency increases. Equation 1-5-1 highlights that a higher pole frequency f_0 increases the error amplifier sensitivity with respect to output voltage AC perturbations. However, the frequency f_0 has to be limited to prevent instability, which causes uncontrollable high frequency noise in the output voltage. Therefore, the loop gain T can be high only at low frequency. The *loop gain cross-over frequency* f_{co} is the upper bound of the frequency range where the magnitude of loop gain T is greater than 1, and is determined by the error amplifier poles f_0, f_P and zero f_Z.

1-8 Closed Loop Output Impedance of the Buck Regulator

The *closed loop output impedance* $Z_{out,CL}$ of the buck regulator is given by the simplified Equation 1-8-1:

Equation 1-8-1

$$\left.\frac{V_{outAC}}{I_{outAC}}\right|_{closed\ loop} = Z_{out,CL} \cong \begin{cases} \dfrac{Z_{out,OL}}{G_{ea}(f)G_c(f)} = \dfrac{R_L V_{rpp}}{V_{inDC}} \dfrac{N_L(f)}{G_{ea}(f)} & f < f_{co} \\ Z_{out,OL} & f > f_{co} \end{cases}$$

According to Equation 1-8-1, the closed loop output impedance $Z_{out,CL}$ of the buck regulator is lower than the open loop output impedance $Z_{out,OL}$ below the cross-over frequency, where $G_{ea}(f)G_C(f) > 1$. Therefore, given the control-to-output gain $G_C(f)$, the buck regulator has better rejection capability of AC load current perturbing effects at frequencies where the error amplifier gain is higher. The error amplifier gain at low frequency is mainly determined by the pole frequency f_0 and by OPAMP DC open loop gain A_{dc}.

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 parameters of a buck regulator determine the nominal value of its DC output voltage?

A. the inductance and capacitance of the L-C filter
B. the reference voltage and the voltage sensor gain
C. the error amplifier pole and OPAMP dc gain A_{dc}

1-2 What parameter of a buck regulator determines its DC output voltage offset error?

A. the inductance L
B. the OPAMP open loop dc gain A_{dc}
C. the error amplifier pole frequency f_0

1-3 What parameter of a buck regulator determines the open loop output impedance of the buck regulator at low frequency?

A. the inductance of the inductor
B. the capacitance pf the capacitor
C. the resistance of the inductor

1-4 What parameters majorly influence the closed loop output impedance of the buck regulator at low frequency?

A. the error amplifier pole frequency f_0 and OPAMP dc gain A_{dc}
B. the MOSFET half-bridge gate driver voltage
C. the reference voltage and the voltage sensor gain

1-5 Based on your answers to Questions 1-1 to 1-4, what would you do to design a buck regulator with higher DC accuracy and low output impedance?

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2 Exercise

The **Discrete Buck Section** in the TI Power Electronics Board for NI ELVIS III is based on the following setup:

- MOSFETs: TI's CSD15380F3, assume V_{th} = 1.35V, β = 0.24A/V^2, λ =0.05V^{-1}
- OPAMP: TI's OPA835IDBVR, assume A_{dc}=10^6, V_{cc+}=5.5V, V_{cc-}=0V.
- VOLTAGE REFERENCE: TI's LM4140, assume V_{ref}=1.024V.
- ERROR AMPLIFER SETUP: f_0 = 4.06kHz.

The TI's devices datasheets are available at the following links:

- CSD15380F3 MOSFET: http://www.ti.com/lit/ds/symlink/csd15380f3.pdf
- OPA835IDBVR OPAMP: http://www.ti.com/lit/ds/symlink/opa835.pdf
- LM4140 VOLTAGE REFERENCE: http://www.ti.com/lit/ds/symlink/lm4140.pdf

The voltage divider is configurable as follows:

- (a) R_{i1}=39.2kΩ, R_g=18.2kΩ;   (b) R_{i1}=39.2kΩ, R_g=10.2kΩ

The L-C filter is configurable as follows:

- (a) L = 15µH, R_L = 140mΩ;   (b) L = 48µH, R_L = 400mΩ;
- (a) C = 10µF, R_c = 5mΩ;   (b) C = 100µF, R_c = 55mΩ.

2-1 Calculate the nominal value of the DC output voltage $V_{outDC,nom}$, in Volts with three decimal digits, and the DC offset error, in microvolts with one decimal digit, with voltage divider options (a) and (b) :

- (a): $V_{outDC,nom}$ = ___________; ERR_{DC} = _______
- (b): $V_{outDC,nom}$ = ___________; ERR_{DC} = _______

2-2 You have a buck regulator powered by a 7V DC source voltage and generating a 5V DC output voltage for a 120Ω DC load resistance R_o. The load is subjected to an AC perturbation $I_{outAC}sin(2\pi ft)$, where the frequency f can have the values listed in Table 2-1. Assume the inductor configuration (b) and the capacitor configuration (a). Calculate the open and closed loop output impedance $Z_{out,OL}$ and $Z_{out,CL}$ in Ohms with three decimal digits, and report the results in Table 2-1.

Table 1-1 Output Impedance of a buck regulator in open loop and closed loop operation.

f [Hz]	1	10	100	1000	10000
$Z_{out,OL}$					
$Z_{out,CL}$					

2-3 Based on the results of your calculations, do you see an improvement in the AC load current perturbation rejection capability of the buck regulator in closed loop operation compared to open loop operation?

A. yes

B. no

Please provide your comments: ____

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2-4 What parameter would you change to further improve the low frequency rejection capability, and how?

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3 Simulate

The simulations you will perform in this section allow you to analyze the closed loop behavior of buck regulator. You will observe the DC output voltage while varying the DC source voltage, to verify the regulation capability of the feedback control loop. You will analyze the PWM control voltage generated by the error amplifier and compare it with the ratio between the DC output and source voltages.

3.1 Instructions

1. Open *Lab8 – Buck Regulator in Closed Loop Operation* from the file path: https://www.multisim.com/content/WSHeUkuHMCHHnyeEu2MHxZ/lab-8-buck-regulator-in-closed-loop-operation/.

   The circuit used for simulating the DC and AC buck regulator closed loop operation is shown in Figure 3-1. The error amplifier generates the PWM control voltage V_c. The load is a DC resistance R_o = 240Ω. The error amplifier poles and zero frequencies are f_0 = 120Hz, f_z = 4.276kHz and f_P = 153.9kHz, with switches Sf2 and Si2 closed. The OPAMP is characterized by a dc gain A_{dc}=10^6. The DC voltage source V_{in} is characterized by a parasitic resistance R_{in} = 100mΩ.

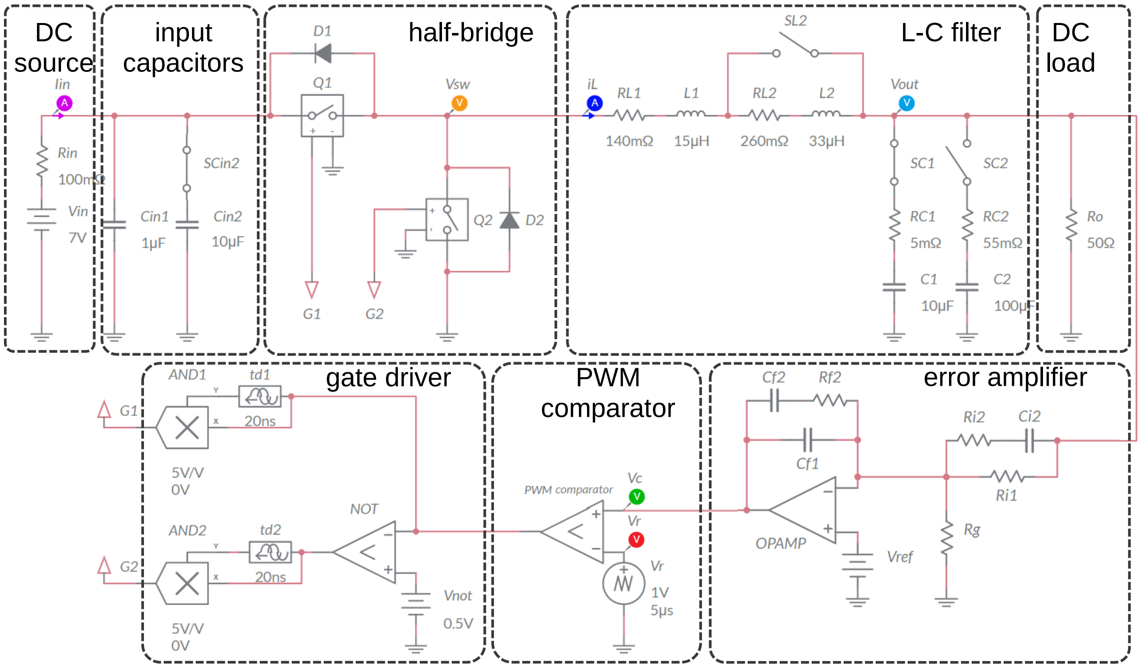

Figure 3-1. Multisim Live Circuit Schematic for the Analysis of Buck Regulator in Closed Loop Operation.

2. Set switches SCin2 and SC1 to be CLOSED, and switches SL2 and SC2 to be OPEN.
3. Set the *initial voltage* of capacitor *C1* to 5V.
4. Select the *Interactive* simulation option and the *Split* visualization option.
5. Set the *Maximum Time Step* and *Maximum Initial Step* to 10ns, and *End time* to 2ms in the *Simulation settings* menu;
6. Check the *Periodic* option box for voltage probes V_{in}, V_{out}, and V_c in the *Measurement labels* menu.
7. Import in Table 3-1 the nominal value $V_{outDC,nom}$ in Volts with three decimal digits, calculated in the ***Exercise*** Section 2-1.
8. Set *DC_mag* = 6.0V for generator V_{in}.
9. Run the simulation and wait until it ends.
10. Read the average value V_{AV} displayed by the output voltage probe V_{out}, in Volt with three decimal digits, and report the result in Table 3-1.
11. Read the average value V_{AV} displayed by the PWM control voltage probe V_c, in Volt with three decimal digits, calculate the ratio V_c/V_{rpp} and report the result in Table 3-1, with three decimal digits.
12. Calculate the ratio V_{outDC}/V_{inDC} with three decimal digits and report the result in Table 3-1.
13. Repeat steps 9-12 for each value of DC source voltage V_{inDC} (*VO* voltage of the generator V_{in}) listed in Table 3-1.

Table 3-1 DC Output Voltage and Error Amplifier Voltage as function of DC Source Voltage.

V_{inDC} [V]	6.0	6.5	7.0	7.5	8.0	8.5	9.0
$V_{outDC,nom}$ [V]							
V_{outDC} [V]							
V_{cDC}/V_{rpp} [V]							
V_{outDC}/V_{inDC}							

3-1-1 Does the DC output voltage V_{outDC} change as V_{inDC} increases?

A. yes

B. no

Discuss the results based on the **Theory and Background** section equations:

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3-1-2 Does the PWM control voltage V_{cDC} change as V_{inDC} increases?

A. yes

B. no

Discuss the results based on the **Theory and Background** section equations:

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3-1-3 How is the ratio V_{cDC}/V_{rpp} correlated to the ratio V_{outDC}/V_{inDC}? why?

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3-1-4 What change do you expect in the simulation results if you close the switch SC2 and open the switch SC1? why?

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Troubleshooting tips:

- If the simulation does not run and you get some error message, reload *Lab8 – Buck Regulator in Closed Loop Operation* from this file path: https://www.multisim.com/content/WSHeUkuHMCHHnyeEu2MHxZ/lab-8-buck-regulator-in-closed-loop-operation/
  and restart the simulation, following the instructions.

4 Implement

The experiments of this section allow you to observe the behavior of a real buck regulator in closed loop operation. First, you will analyze the DC operating point of the buck regulator while varying the DC source voltage. Next, you will measure the AC output voltage perturbation generated by an AC load current perturbation. 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.

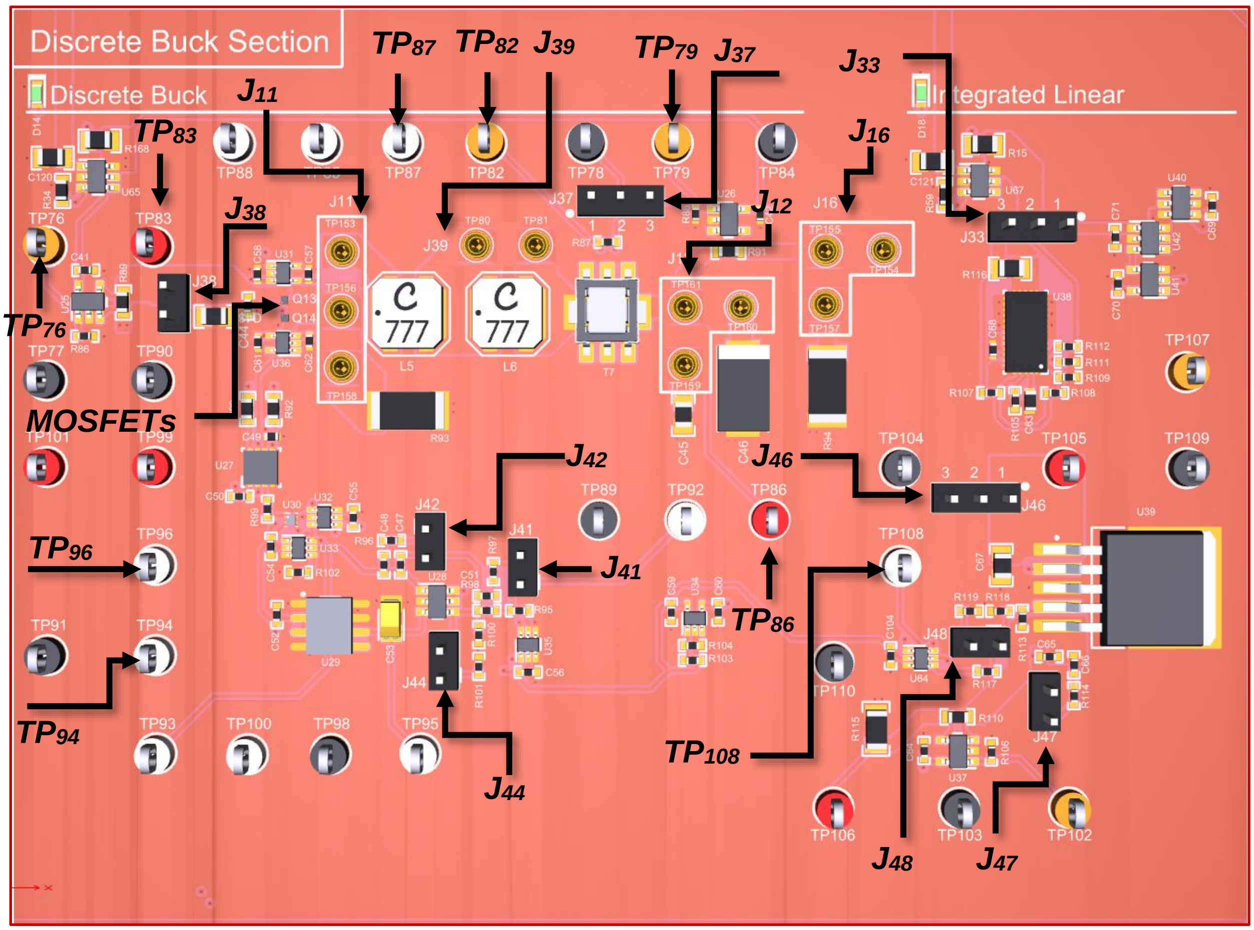

Figure 4-1. TI Power Electronics Board for NI ELVIS III - Discrete Buck Section Used for the Analysis of Buck Regulator in Closed Loop Operation

The half-bridge MOSFETs is implemented with TI's CSD15380F3, the error amplifier OPAMP is TI's OPA835IDBVR, the PWM comparator uses a TI's TLV7011DPWR, the gate driver is a TI's TPS51601ADRBR. The INA139NA/3K current shunt monitor senses the low frequency output current, which can be measured at test point TP79 with a 1:1 Ampère/Volt transduction gain. The links to datasheets are available below:

- CSD15380F3 MOSFET: http://www.ti.com/lit/ds/symlink/csd15380f3.pdf;
- OPA835IDBVR OPAMP: http://www.ti.com/lit/ds/symlink/opa835.pdf;
- TLV7011DPWR COMPARATOR: http://www.ti.com/lit/ds/symlink/tlv7011.pdf;
- TPS51601ADRBR GATE DRIVER: http://www.ti.com/lit/ds/symlink/tps51601a.pdf;
- INA139NA/3K CURRENT MONITOR: http://www.ti.com/lit/ds/symlink/ina139.pdf.

The MOSFETs on-state resistance is 1.2Ω at 4.5V gate-to-source voltage. The half-bridge is connected to the L-C filter through jumper J11. The output of the L-C filter is connected to the input of an **Integrated Linear Regulator**, which operates as a dynamic load, through jumper J16. 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).

The error amplifier poles and zero frequencies are set to f_0 = 120Hz, f_z = 4.27kHz and f_P = 153.9kHz, with jumpers J41 and J42 closed. [**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 *Variable Power Supply*, *Function Generator* and *Oscilloscope* 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 Linear 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 *Lab8 – Buck Regulator in Closed Loop Operation*.
5. Configure the jumpers of the board as indicated in Table 4-1.

Table 4-1 Jumpers configuration

J11	J12	J16	J33	J37	J38
short TP156-TP153	short TP159-TP161	short TP155-TP154	short 2-3	short 1-2	short

J39	J41	J42	J44	J46	J47	J48
open	short	short	short	short 1-2	short	open

4-2 Experiment 1 Instructions

1. Connect the instruments as indicated in Table 4-2-1.

Table 4-2-1 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 TP93 (V_c), connect CH-4 to TP87 (V_{sw})
Function Generator	connect CH-1 to FGEN1 BNC connector (TP94 = Buck PWM comparator V_r) connect CH-2 to FGEN2 BNC connector (TP108 = Linear Feedback V_{FB})

2. Configure and setup the instruments as indicated in Table 4-2-2.

Table 4-2-2 Recommended Instruments Configuration and setup for Experiment 1

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive			
Oscilloscope	*Trigger*: analog edge, CH-4, set to 50%	*Horizontal*: 200ms/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 2V/div • offset 0.0V	*Channel 2*: ON • DC coupling • 2V/div • offset 0.0V	*Channel 3*: ON • DC coupling • 2V/div • offset -8.0V	*Channel 4*: ON • DC coupling • 2V/div offset 0.0V
Function Generator	*Channel 1*: Triangle, Frequency 500kHz, Amplitude 6Vpp, DC offset 3.0V *Channel 2*: Sine, Frequency 1Hz, Amplitude 0.0Vpp, DC offset -2.0V			

3. Run *Oscilloscope*, *Function Generator* and *Power Supply*.
4. Using the *Oscilloscope* cursors in Track mode, read the average DC values of the CH-2 (V_{out}), in Volt with two decimal digits, and report the value in Table 4-2-3.
5. Using the *Oscilloscope* cursors in Track mode, read the average DC values of the CH-3 (V_c), in Volt with two decimal digits, divide it by the triangular carrier peak-peak amplitude V_{rpp} = 6V, and report the result, with two decimal digits, in Table 4-2-3.
6. Repeat the measurements and calculations for all the values of the source voltage V_{inDC} indicated in Table 4-2-3, by changing the DC voltage of *Power Suppy*.
7. Import in Table 4-2-3 the DC values of V_{outDC} and V_{cDC}/V_{rpp} collected in Table 3-1, with two decimal digits.
8. Stop *Power Supply*, *Function Generator* and *Oscilloscope*.

Table 4-2-3 DC Output Voltage and Error Amplifier Voltage as function of DC Source Voltage.

V_{inDC} [V]	6.0	6.5	7.0	7.5	8.0	8.5	9.0
$V_{outDC,nom}$ [V]							
V_{outDC} [V] measured							
V_{outDC} [V] from Table 3-1							
V_{cDC}/V_{rpp} [V] measured							
V_{cDC}/V_{rpp} [V] from Table 3-1							

4-2-1 Does the DC output voltage V_{outDC} vary as V_{inDC} increases?

A. yes

B. no

Discuss the differences between simulations and experiments based on the **Theory and Background** section equations:

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4-2-2 What is the trend of the ratio V_{cDC}/V_{rpp} as V_{inDC} increases? why?

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4-2-3 Based on your answer to Questions and 4-1-1 and 4-1-2, what parameter of the buck regulator model would you change to improve the accuracy of simulations? How and why?

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4-3 Experiment 2 Instructions

1. Connect the instruments as indicated in Table 4-3-1.

Table 4-2-1 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 TP93 (V_c), connect CH-4 to TP79 (I_{out})
Function Generator	connect CH-1 to FGEN1 BNC connector (TP94 = Buck PWM comparator V_r) connect CH-2 to FGEN2 BNC connector (TP108 = Linear Feedback V_{FB})
Digital Multimeter	connect Voltage input to TP79 (I_{out})

2. Use the instruments configuration and setup shown in Table 4-3-1.

Table 4-3-1 Recommended Instruments Configuration and setup for Experiment 2

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive			
Oscilloscope	*Trigger*: Immediate	*Horizontal*: 200µs/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 2V/div • offset 0.0V	*Channel 2*: ON • DC coupling • 10mV/div • offset -5.0V	*Channel 3*: ON • DC coupling • 10mV/div • offset -4.33V	*Channel 4*: ON • DC coupling • 10mV/div offset 0.0V
Function Generator	*Channel 1*: Triangle, Frequency 500kHz, Amplitude 6Vpp, DC offset 3.0V *Channel 2*: Sine, Frequency 1Hz, Amplitude 1Vpp, DC offset 550mV			
Digital Multimeter	*Measurement mode*: DC voltage; *Range*: Automatic			

3. Run *Oscilloscope*, *Function Generator* and *Power Supply*.
4. Read the DC average of output voltage V_{outDC} and PWN control signal V_{cDC} on the *Oscilloscope* CH-2 (V_{out}) and CH-3 (V_c), in Volts with all decimal digits shown by the instrument, and report the values in Table 4-3-2.
5. Read the peak-peak amplitude of output voltage ΔV_{outpp} and PWN control signal ΔV_{cpp} on the *Oscilloscope* CH-2 (V_{out}) and CH-3 (V_c), in milli Volts with all decimal digits shown by the instrument, and report the values in Table 4-3-2.
6. Calculate the error amplifier gain $G_{ea} = \Delta V_{cpp}/\Delta V_{outpp}$, in with three decimal digits, and report the result in Table 4-3-2.
7. Read the DC average output current I_{outDC} on *Digital Multimeter*, in milli Volt, with one decimal digit, and report the value in Table 4-3-2 in mA with one decimal digit.
8. Read the peak-peak amplitude of output current ΔI_{outpp} on the *Oscilloscope* CH-4 (I_{out}), in milli Volt with all decimal digits shown by the instrument, and report the value in milli Ampère in Table 4-3-2.

9. Calculate the output impedance $Z_{out,CL} = \Delta V_{outpp}/\Delta I_{outpp}$, in Ohm with three decimal digits, and report the result in Table 4-3-2.
10. Repeat the steps 2-6 for all the values of Frequency of the *Function Generator* CH-2 indicated in Table 4-3-2.
11. Stop *Power Supply*, *Function Generator* and *Oscilloscope*.

Table 4-3-2 Buck Regulator Closed Loop Output Impedance.

Function Generator CH-2 Frequency [Hz]	1	10	100	1000
$V_{outDC,nom}$ [V]				
V_{outDC} [V]				
ΔV_{outpp} [mV]				
V_{cDC} [V]				
ΔV_{cpp} [mV]				
$G_{ea} = \Delta V_{cpp}/\Delta V_{outpp}$				
I_{outDC} [mA]				
ΔI_{outpp} [mA]				
$Z_{out,CL} = \Delta V_{outpp}/\Delta I_{outpp}$ [Ω]				

4-3-1 Discuss the trend you observe in the values of the error amplifier gain as the frequency f increases, based on **Theory and Background** section concepts:

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4-3-1 Discuss the trend you observe in the values of the closed loop output impedance as the frequency f increases, based on **Theory and Background** section concepts:

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4-3-3 Based on your answer to Questions and 4-3-1 and 4-3-2, what parameter of the buck regulator would you change to reduce the output impedance? How and why?

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Troubleshooting tips:

- If the simulated and measured results do not match, verify the setup and connections of instruments, and restart the experiment.

5 Analyze

5-1 Re-calculate the theoretical values of error amplifier gain G_{ea} and of closed loop output impedance $Z_{out,CL}$, based on **Theory and Background** equations, using the values of switching frequency (f_s=500kHz) and peak-peak amplitude of the PWM triangular carrier signal (V_{rpp}=6Vpp) adopted for the Experiment 2 of Section 4-2. Graph the resulting values versus the frequency f, together with the experimental values of G_{ea} and $Z_{out,CL}$ collected in Table 4-3-3. Include a legend indicating which line style corresponds to which series (calculations, measurements).

Table 5-1 Closed Loop Power Supply Rejection Ratio.

Frequency [Hz]	1	10	100	1000
theoretical G_{ea}				
experimental G_{ea}				
theoretical $Z_{out,CL}$ [Ω]				
experimental $Z_{out,CL}$ [Ω]				

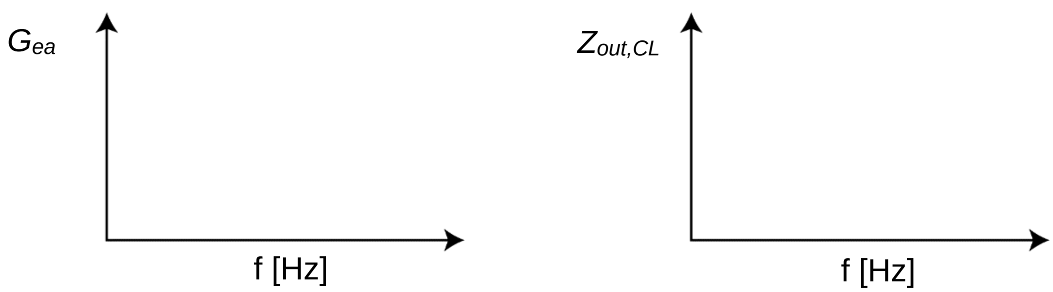

Figure 5-1 Theoretical and Experimental Values of Error Amplifier Gain and Closed Loop Output Impedance of Buck Regulator.

5-2 Discuss the differences you observe between the experimental and theoretical values of error amplifier gain G_{ea} and of closed loop output impedance $Z_{out,CL}$. Based on your learning, assess what parameters majorly influence the two functions G_{ea} and $Z_{out,CL}$, and indicate what parameter would you change to improve the accuracy of the theoretical predictions.

6 Conclusion

6-1 Summary

Write a summary of what you observed and learned about the closed loop operation of a buck regulator, concerning its DC accuracy and rejection capability of load current AC perturbations. Discuss the conditions and the parameters influencing the closed loop operation of the buck regulator, and discuss why and how can you reduce the output impedance of buck regulator.

6-2 Expansion Activities

6-2-1. Investigate the influence of switching frequency on closed loop output impedance of buck regulator, by means of TI Power Electronics Board for NI ELVIS III of Figure 4-1.

a. Follow general instructions provided in Section 4-1.
b. Follow the instructions for Experiment 2 provided in Section 4-3.
c. Set the switching frequency to 200kHz by means of the Frequency of *Function Generator* CH-1.
d. Run the experiment and report the resulting values of closed loop output impedance in Table 6-1.
e. Repeat step d. for all the values of the switching frequency listed in Table 6-1.

Table 6-1 Buck Regulator Closed Loop Output Impedance under different switching frequency conditions

load current AC frequency [Hz]	1	10	100	1000
$Z_{out,CL}$ @ f_s = 200kHz [Ω]				
$Z_{out,CL}$ @ f_s = 400kHz [Ω]				
$Z_{out,CL}$ @ f_s = 600kHz [Ω]				
$Z_{out,CL}$ @ f_s = 800kHz [Ω]				

6-1 Analyze the values of closed loop output impedance as the switching frequency increases and discuss them based on ***Theory and Background*** equations:

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6-2-2. Investigate the influence of the L-C filter setup on closed loop output impedance of buck regulator, by means of TI Power Electronics Board for NI ELVIS III of Figure 4-1.

a. Follow general instructions provided in Section 4-1.
b. Follow the instructions for Experiment 2 provided in Section 4-3.

c. Import in Table 6-2 the values of closed loop output impedance recorded in Table 4-3-2 for Experiment 2, relevant to the setup of jumper J39 open (L = 48µH, R_L = 400mΩ) and jumper J12 shorting TP161-TP159 (C = 10µF, R_c = 5mΩ).
d. Short the jumper J39 to set L = 15µH, R_L = 160mΩ, run the experiment and report the resulting values of closed loop output impedance in Table 6-1.
e. Open the jumper J39 to set L = 48µH, R_L = 400mΩ, short TP161-TP160 with jumper J12 to set C = 100µF, R_c = 55mΩ, run the experiment and report the resulting values of closed loop output impedance in Table 6-2.
f. Short the jumper J39 to set L = 15µH, R_L = 160mΩ, run the experiment and report the resulting values of closed loop output impedance in Table 6-2.

Table 6-2 Buck Regulator Closed Loop Output Impedance under different L-C filter setup conditions

load current AC frequency [Hz]	1	10	100	1000
$Z_{out,CL}$ @ L = 48µH, C = 10µF [Ω]				
$Z_{out,CL}$ @ L = 15µH, C = 10µF [Ω]				
$Z_{out,CL}$ @ L = 48µH, C = 100µF [Ω]				
$Z_{out,CL}$ @ L = 15µH, C = 100µF [Ω]				

6-2 Analyze the values of closed loop output impedance for the different L-C filter configurations and discuss them based on ***Theory and Background*** equations:

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6-3 Resources for learning more

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