ECEN 438/738– Power Electronics Spring 2025

Lab 3: Buck Converter: Open Loop

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The goal of this lab is to investigate the behavior of MOSFETs when configured as a half-bridge in Pulse Width Modulation (PWM) operation. The PWM MOSFETs half-bridge is the main functional element of the buck converter, the most diffused high-efficiency step-down DC-DC regulator topology. First, we review the principle of operation and fundamental equations of the MOSFET in the half-bridge configuration and of the PWM modulator. Next, we predict the theoretical average output voltage of the half-bridge considering the impact of MOSFETs resistance. Then, we simulate the MOSFET half-bridge and PWM modulator and we verify the theoretical predictions in different operating conditions. Finally, we perform lab experiments to measure the real values of output voltage and duty-cycle, determine the buck regulator conversion ratio, evaluate the MOSFETs loss and resistance and determine the efficiency of the regulator.

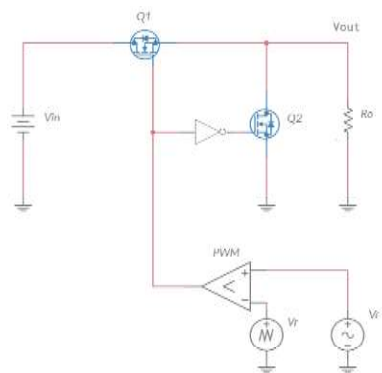

Figure 1-1. MOSFETs in Half-Bridge Configuration

Learning Objectives

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

1. Given a MOSFET half-bridge, a PWM modulator, a source voltage, and a load resistance, you will calculate the PWM control voltage required to achieve a desired output voltage and the conversion efficiency of the half-bridge in different operating conditions, with specified units and accuracy.
2. Given a MOSFET half-bridge, a PWM modulator with a triangular carrier signal and a DC control voltage, you will simulate the half-bridge behavior to verify the consistency of theoretical predictions, by comparing the simulated and the calculated output voltage under the same source voltage and a load resistance conditions.
3. Given a real MOSFET half-bridge, a PWM modulator, a DC power supply, a load resistor, and a two channel function generator, you will determine the PWM control voltage needed to achieve a desired output voltage, the duty-cycle, the efficiency and the MOSFET on-state resistance, 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 a PWM modulated MOSFET half-bridge. This important element is used in a large variety of switching power supply applications, ensuring high-efficiency DC-DC voltage conversion.

1-2 MOSFET half-bridge in PWM operation.

Figure 1-2 shows a couple of MOSFETs Q_1 and Q_2 in half-bridge configuration, controlled by a PWM modulator. The MOSFETs operate as switches. The *carrier* signal V_r, and the *control* signal V_c determine the status of the PWM comparator output. When $V_r < V_c$, the PWM comparator output is high, the Gate Driver sets gate signals G1 and G2 respectively high and low, and Q1 conducts whereas Q2 is open. When $V_r > V_c$, the PWM comparator output is low, the Gate Driver sets gate signals G1 and G2 respectively low and high, and Q1 is open whereas Q2 conducts. This results in a square-wave half-bridge output voltage V_{out}, as shown in Figure 1-2 [**Note:** the edges of the square-wave voltage V_{out} in a real PWM modulated half-bridge are delayed with respect to the crossing of V_c and V_r signals]. The switching frequency $f_s = 1/T_s$ is determined by the period T_s of the signal V_r.

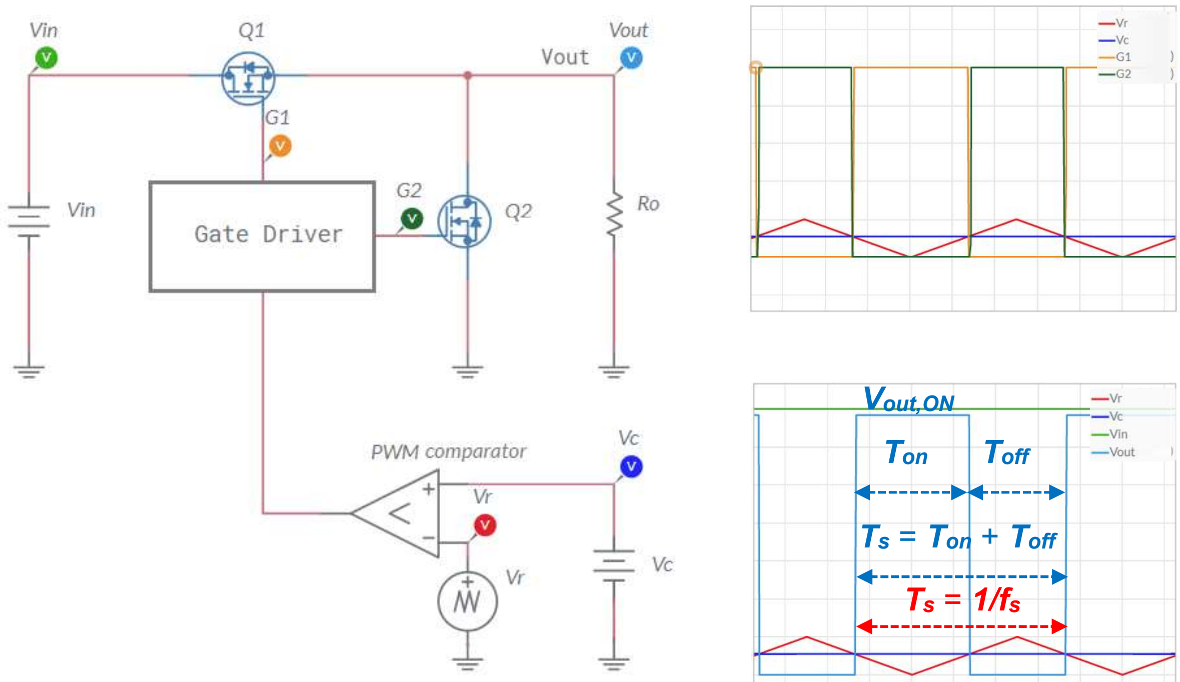

Figure 1-2. MOSFET Half-Bridge in PWM Operation.

The amplitude $V_{out,ON}$ of the square-wave voltage V_{out} is determined by the input voltage V_{in} and by the MOSFET characteristics. During the time the gate signal of a MOSFET is high, the gate-drive circuitry drives the device to the ohmic region, where it behaves like a resistor (see **Lab1**). The MOSFET drain-to-source on-state resistance $R_{DS(on)}$ in the ohmic region is inversely proportional to the gate-to-source voltage, and depends on the temperature, as shown in Figure 1-3.

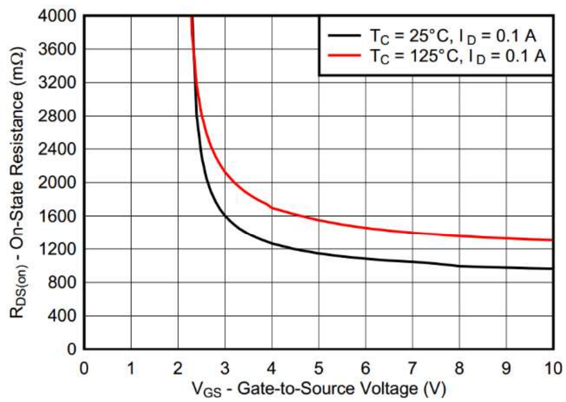

Figure 1-3. MOSFET On-State Resistance as Function of Gate-to-Source Voltage (Texas Instruments CSD15380F3).

An approximated analytical expression of the on-state resistance $R_{DS(on)}$ of a MOSFET is given by Equation 1-1:

Equation 1-1

$$R_{DS(on)} = \frac{1}{\beta(V_{gs} - V_{th})}$$

where V_{gs} is the gate-to-source voltage applied to the MOSFET, V_{th} is its gate-to-source voltage threshold, and β is its trans-conductance coefficient (see **Lab1**).

1-3 Average Output Voltage of MOSFET Half-Bridge

The voltage V_{out} applied to the load resistor R_o is given by Equation 1-2:

Equation 1-2

$$V_{out} = \begin{cases} V_{out,ON} = \dfrac{R_o}{R_o + R_{DS(on)}^{Q1}} V_{in} & t \in T_{on} \\ V_{out,OFF} = 0 & t \in T_{off} \end{cases}$$

where T_{on} is the interval of time where $V_r < V_c$, T_{off} is the interval of time where $V_r > V_c$, and $T_{on} + T_{off} = T_s$. The ratio $D = T_{on}/T_s$ is the PWM duty-cycle D. The duty-cycle D is determined by ratio between the control signal and the peak-peak amplitude of the triangular carrier signal, and is given by:

Equation 1-3

$$D = \begin{cases} 0 & V_c \le 0 \\ \dfrac{V_c}{V_{rpp}} & 0 < V_c < V_{rpp} \\ 1 & V_c \ge V_{rpp} \end{cases}$$

Based on Equation 1-2, the average voltage applied to the load resistor $V_{out,AV}$ is:

Equation 1-4

$$V_{out} = \frac{R_o}{R_o + R^{Q1}_{DS(on)}} D V_{in}$$

Based on Equations 1-3 and 1-4, the average output voltage $V_{out,AV}$ can range from 0 to $V_{in}R_o/(R_o + R^{Q1}_{DS(on)}) < V_{in}$. From Equation 1-4 we can derive the value of the control signal V_c required to achieve a desired nominal average output voltage $V_{out,nom}$:

Equation 1-5

$$V_c = \left(1 + \frac{R^{Q1}_{DS(on)}}{R_o}\right) \frac{V_{rpp} V_{out,nom}}{V_{in}}$$

1-4 MOSFET Power Loss and Half-Bridge Conversion Efficiency

The conduction average power loss of MOSFET Q1 is given by:

Equation 1-6

$$P_{Q1} = D R^{Q1}_{DS(on)} \frac{V_{in}^2}{(R^{Q1}_{DS(on)} + R_o)^2}$$

The maximum MOSFET power loss is given by $P_{Q1max}=(150°C-T_a)/R_{\theta ja}$, where T_a and $R_{\theta ja}$ are the ambient temperature and the MOSFET thermal resistance, respectively. The average power P_{Ro} delivered to the load resistor R_o and the resulting percent efficiency $\eta_{\%}$ of the MOSFET half-bridge are given by:

Equation 1-7

$$P_{Ro} = D R_o \frac{V_{in}^2}{(R^{Q1}_{DS(on)} + R_o)^2}$$

Equation 1-8

$$\eta_{\%} = \frac{R_o}{R_o + R^{Q1}_{DS(on)}} x100$$

Equation 1-7 highlights that the MOSFET half-bridge can achieve a very high efficiency if the resistance $R^{Q1}_{DS(on)}$ of MOSFET Q1 is very low. According to the MOSFET on-state resistance of Figure 1-3, a higher value of the gate-driver voltage can help reducing the on-state resistance.

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 functional element is used to change the average output voltage of a MOSFET half-bridge?

A. the MOSFET gate driver
B. the PWM modulator
C. the voltage source

1-2 How is average output voltage of the half-bridge related to the source voltage?

A. it is always lower
B. it is always higher
C. it can be higher or lower

1-3 Given the source voltage and the load resistance, how can we change the value of the average output voltage of the half-bridge?

A. by varying the gate-driver voltage
B. by varying the PWM modulator control voltage
C. by varying the gate-driver voltage and the PWM modulator control voltage

1-4 Is the average output voltage of the half-bridge influenced by the switching frequency?

A. yes
B. no
C. it depends on the MOSFET on-state resistance

1-5 What factor is mainly influencing the efficiency of the half-bridge?

A. the duty-cycle
B. the carrier peak-peak voltage
C. the MOSFET power loss

1-6 How can we reduce the MOSFET conduction power loss?

A. by increasing the PWM comparator control voltage
B. by increasing the gate-driver voltage
C. by decreasing the gate-driver voltage

2 Exercise

The two TI's CSD15380F3 (http://www.ti.com/lit/ds/symlink/csd15380f3.pdf) N-channel MOSFETs Q1 and Q2 used in the Discrete Buck Section of the TI Power Electronics Board for NI ELVIS III have the following nominal parameters: V_{th} = 1.1V, β = 0.24A/V^2, λ =0.02V^{-1}. The negative input of the PWM modulator is connected to a voltage source generating a triangular waveform, with 2μs period T_s, equal rise and fall time, 1V peak-peak voltage, while the positive input is connected to a DC voltage source. The MOSFETs Gate Driver provides a 5V gate-to-source voltage V_{dr}.

2-1 Assuming V_{in} = 7V, use the rules and equations provided in the **Theory and Background** section to calculate:

- the MOSFET on-state resistance $R_{DS(on)}$, in Ohms with three decimal digits: $R_{DS(on)}$ = ____________
- the control voltage, in Volt with three decimal digits, required to achieve an average output voltage $V_{out,AV}$ = 2.5V, for all the values of load resistance R_o listed in Table 2-1, and the corresponding % efficiency, with one decimal digit.

Table 1-1 PWM control voltage and efficiency as function load resistance

R_o [Ω]	20	50	100	120	150	200
V_c [V]						
η [%]						

2-2 Assuming R_o= 50Ω, use the equations provided in the **Theory and Background** section to calculate the control voltage, in Volt with three decimal digits, required to achieve an average output voltage $V_{out,AV}$ = 2.5V, for all the values of source voltage V_{in} listed in Table 2-1, and the corresponding % efficiency, with one decimal digit.

Table 2-2 PWM control voltage and efficiency as function input voltage

V_{in} [Ω]	1	2	3	4	5	6
V_c [V]						
η [%]						

3 Simulate

The goal of the simulations you will perform in this section is to analyze the operation of a MOSFET half-bridge controlled by a PWM modulator. You will verify the consistency of the PWM modulator control voltage calculated in the **Exercise** Section, by observing the average voltage at the output of the half-bridge, under different source voltage and load resistance conditions.

3-1 General Instructions

1. Open *Lab5 – Buck Regulator Half-Bridge PWM Operation* from this file path: https://www.multisim.com/content/sRY9ZW7saFpr4MKWu2a5A5/lab-5-buck-regulator-mosfets-pwm-operation/
   The circuit schematic for the analysis of the PWM modulated MOSFET half-bridge is shown in Figure 3-1. The MOSFETs are modeled by means of two *Single Pole Single Throw (SPST)* switches, characterized by 1.068Ω ON resistance and 1MΩ OFF resistance. The gate driver block includes time delays *td1* and *td2* and gates AND1 and AND2 to prevent cross conduction of the MOSFETs Q1 and Q2.

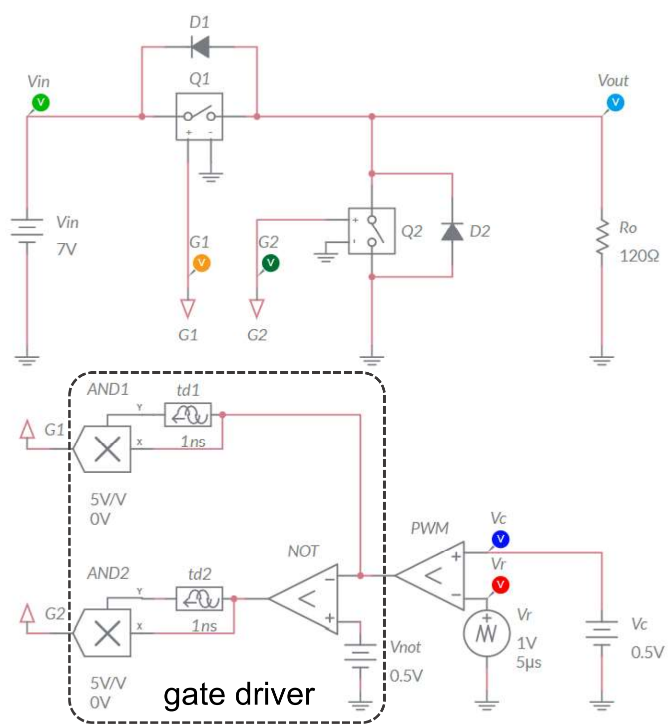

Figure 3-1. Multisim Live Circuit Schematic for the Analysis of a buck regulator in open loop DC Operation

3-1-1 Simulation 1 Instructions

1. Select *Interactive* simulation and *Split* visualization options.

2. Check the *Periodic* option box for voltage probe V_{out} in *Measurement labels* menu.
3. Import in Table 3-1 the values of PWM control voltage V_c you have calculated and reported in Table 2-1 of **Exercise** section for each value of the load resistance R_o;
4. 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: 20Ω;
   - V_c: *DC_mag* = value of V_c corresponding to R_o equal to 20Ω.
5. Run the simulation, 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.
6. Export the *Grapher image* and save it as `Lab 5 - Buck Regulator_ Half-Bridge PWM Operation-Grapher_xx_yy.png`, where xx is the R_o value and yy is the V_c value.
7. Repeat steps 6-7 for all the values of R_o and V_c listed in Table 3-1.
8. Stop the simulation

Table 3-1 Average output voltage in load resistance and PWM control voltage matched conditions

R_o [Ω]	20	50	100	120	150	200
V_c [V] from Table 2-1						
$V_{out,AV}$ [V]						

3-1-2 Simulation 2 Instructions

1. Check the *Periodic* and the *Instantaneous* option boxes for voltage probe V_{out} in *Measurement labels* menu.
2. Import in Table 3-2 the values of PWM control voltage V_c you have calculated and reported in Table 2-2 of **Exercise** section for each value of the source voltage V_{in};
3. Set the simulation circuit parameters as follows:
   - R_o: 50Ω;
   - V_r: *VA* = 1V, *Per* = 5µs, *TF* = 2.5µs, Offset 0V;
   - V_{in}: *DC_mag* = 1.0V;
   - V_c: *DC_mag* = value of V_c corresponding to V_{in} equal to 1V.
4. Run the simulation, 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 [**Note:** if the V_{AV} value is not displayed, read the *v* (instantaneous) value displayed by the output voltage probe V_{out}].
5. Export the *Grapher image* and save it as `Lab 5 - Buck Regulator_ Half-Bridge PWM Operation-Grapher_xx_yy.png`, where xx is the V_{in} value and yy is the V_c value.

6. Repeat steps 6-7 for all the values of V_{in} and V_c listed in Table 3-1.
7. Stop the simulation

Table 3-2 PWM control voltage required to set 2.5V output voltage as a function of source voltage.

V_{in} [Ω]	1	2	3	4	5	6
V_c [V] from Table 2-2						
$V_{out,AV}$ [V]						

3-1 Does the average output voltage match the required value in all the source voltage and load resistance conditions?

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

____

3-2 From the images you have saved in step 5, does the duty-cycle of the square-wave output voltage V_{out} always increase as the control voltage V_c increases?

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

____

Troubleshooting tips:

- If the simulation does not converge and you get some error message, reload *Lab5 – Buck Regulator Half-Bridge PWM 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 you perform in this section allow you to observe the behavior of a real MOSFET half-bridge in PWM operation. You will measure the ON and OFF times, voltages and currents characterizing the operation of the half-bridge under different conditions. Then, you will calculate the duty-cycle and the efficiency. Finally, you will estimate the MOSFETs on-state resistance. 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 maximum input voltage V_{in} is 12V]. A 50Ω resistance R_o can be connected to the output of the Half-bridge (test point TP87) by means of the Jumper J11. The TI's CSD15380F3 half-bridge MOSFETs are characterized by a typical 1.2Ω on-state resistance at 4.5V gate-to-source voltage, 25°C and 0.1A, and a thermal resistance of 255°C/W. The PWM modulator is based on TI's TLV7011DPWR comparator, while the half-bridge MOSFET gate driver is a TI's TPS51601ADRBR.

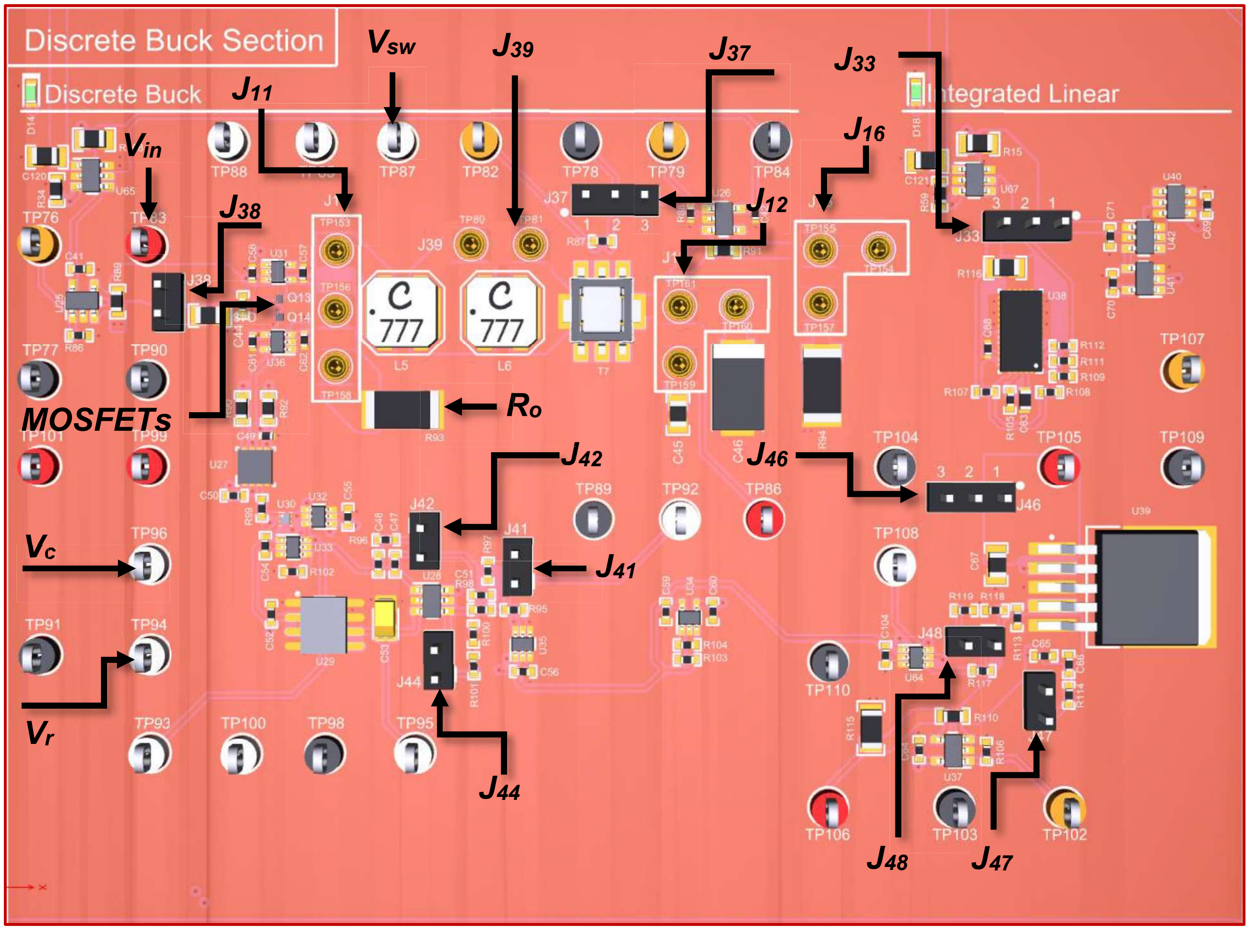

Figure 4-1. TI Power Electronics Board for NI ELVIS III - Discrete Buck Section Used for the Analysis of MOSFET Half-Bridge PWM Operation.

The datasheets of TI's components are available at these links:

- 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 PWM modulator triangular carrier signal V_r and control signal V_c are available at test points TP94 and TP96, respectively. [**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 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 *Lab5 – Buck Regulator Half-Bridge PWM Operation*.
5. Configure the jumpers of the board as indicated in Table 4-1.
6. Connect and configure the instruments as indicated in Tables 4-2 and 4-3.

Table 4-1 Jumpers setup

J11		J12	J16	J37	J38	J39
short TP156-TP158		open	open	short 1-2	short	open
J41	J42	J33	J44	J46	J47	J48
short	short	short 2-3	open	short 2-3	short	open

Table 4-2 Instruments Connections

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

Table 4-3 Recommended Instruments Configuration and setup

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive			
Oscilloscope	*Trigger*: Analog Edge, CH-2, set to 50%	*Horizontal*: 2us/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 1V/div • offset 0V	*Channel 2*: ON • DC coupling • 2V/div • offset 0V	*Channel 3*: ON • DC coupling • 1V/div • offset 0V	*Channel 4*: ON • DC coupling • 1V/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 0V
Digital Multimeter	*Measurement mode*: DC voltage; *Range*: Automatic

7. Run *Oscilloscope*, *Digital Multimeter*, *Function Generator* and *Power Supply*.
8. Connect the *Digital Multimeter* input to TP87 (V_{sw})
9. Adjust the *Function Generator* CH-2 DC offset until the measurement of *Digital Multimeter* equals 4.000V, with three decimal digits, and then record the resulting value of the control voltage V_c, in Volt with three decimal digits, in Table 4-4.
10. Using ***Theory and Background*** equations, calculate the value, in Volt with three decimal digits, of the control voltage required to achieve the same average output voltage, and report the result in Table 4-4.
11. Use the horizontal cursors to measure the values of ON time, T_{on}, and OFF time, T_{off}, in micro seconds with two decimal digits, and report the results in Table 4-4.
12. Calculate the percent duty-cycle $D = T_{on} / (T_{on} + T_{off}) \times 100$, with no decimal digits, and report the value in Table 4-4.
13. Use the vertical cursors to measure the values of output voltage $V_{out,ON}$ and $V_{out,OFF}$ during the ON time and OFF time, in Volt with at least two decimal digits, and report the results in Table 4-4.
14. Calculate the average output power $P_{out,AV} = D(V_{out,ON})^2/R_o$, in Watt with three decimal digits, and report the result in Table 4-4.
15. Connect *Digital Multimeter* to TP76 to measure the average input current $I_{in,AV}$, read the measurement in Volt (the current sensor on board has 1V/A gain), with three decimal digits, and report the result in Table 4-4.
16. Use the vertical cursors to measure the average value of input voltage $V_{in,AV}$, in Volt with three decimal digits, calculate the average input power $P_{in,AV} = V_{in,AV} \times I_{in,AV}$, in Watt with three decimal digits, and report the result in Table 4-4.
17. Calculate the percent efficiency $\eta = P_{out} / P_{in} \times 100$, with one decimal digit, and report the result Table 4-4.
18. Calculate the value of the load resistor current $I_{o,ON} = V_{out,ON} / R_o$ during the ON time T_{on}, in Ampère with three decimal digits, and report the results in Table 4-4.
19. Calculate the on-state resistance of MOSFET Q1 (high side) $R_{ds(on)} = (V_{in} - V_{out,ON}) / I_{o,ON}$, in Ohm with no decimal digits, and report the result in Table 4-4.
20. Using Equation 1-6, calculate the power loss P_{Q1} of the MOSFET Q1 (high side), in Watt with three decimal digits, and report the result in Table 4-4.
21. Repeat the steps 8-20 for all the values of output voltage V_{out} listed in Table 4-4.
22. Stop *Power Supply*, *Function Generator*, *Digital Multimeter* and *Oscilloscope*.

Table 4-4 Half-Bridge PWM operation.

$V_{out,AV}$ [Ω]	4	5	6
V_c [V]			
V_c [V] from Theory			
T_{ON} [μs]			
T_{OFF} [μs]			
duty-cycle [%]			
$V_{out,ON}$ [V]			
$V_{out,OFF}$ [V]			
$P_{out,AV}$ [W]			
$I_{in,AV}$ [A]			
$P_{in,AV}$ [W]			
η [%]			
$I_{o,ON}$ [A]			
$Q1\ R_{ds(on)}$ [Ω]			
$Q1\ P_{loss}$ [W]			

4-1 Are the values of the control voltage you have set to achieve the desired output voltage higher or lower than the calculated values?

A. higher
B. lower
C. other: ______________________________

Please provide your comment: ______________________________

____

4-2 How does the efficiency change as the output voltage increases?

A. it increases
B. it decreases
C. other: ______________________________

Please provide your comment: ______________________________

____

Troubleshooting tips:

- If the MOSFET half-bridge 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 Graph the values of the voltage conversion ratio $M = V_{out,AV}/V_{in}$ between the average output voltage $V_{out,AV}$ collected in Table 4-4 and the average input voltage V_{in}, as function of the percent duty-cycle D:

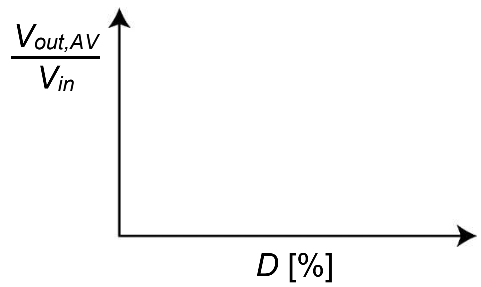

Figure 5-1 Voltage Conversion Ratio of the Half-Bridge as Function of Duty-Cycle.

5-2 Describe the trend of the conversion ratio M you observe, and discuss it based on ***Theory and Background*** equations:

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5-3 Graph the values of the % efficiency as function of the average output voltage $V_{out,AV}$ collected in Table 4-4:

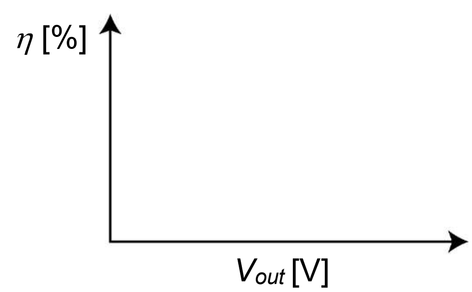

Figure 5-2 Efficiency of the Half-Bridge as Function of Output Voltage.

5-4 Describe the trend of the efficiency you observe, and discuss it based on ***Theory and Background*** equations:

5-5 Graph the values of the MOSFET on-state resistance $R_{ds(on)}$ as function of the power loss P_{loss} collected in Table 4-4:

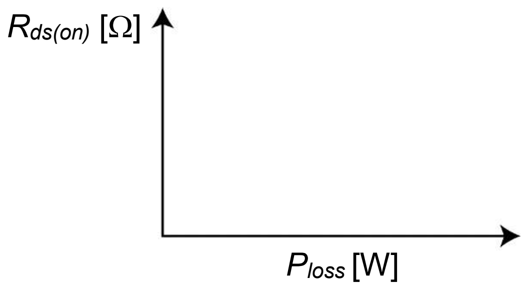

Figure 5-3 MOSFET On-State Resistance as function of power loss.

5-6 Describe the trend of the MOSFET on-state resistance you observe, and discuss it based on ***Theory and Background*** equations:

6 Conclusion

6-1 Summary

Write a summary of what you observed and learned about the operation of a PWM MOSFET half-bridge, and the impact of the MOSFET on-state resistance on its overall performances. Explain the limits of operation in terms of admissible ranges of values of input and output voltage and current, considering the inherent properties of the half-bridge, of the PWM modulator and of the MOSFETs.

6-2 Expansion Activities

6-2-1. Investigate how the switching frequency influences the PWM operation, by means of simulations and measurements.

- Simulations
  a. Set the source voltage V_{in} at 7V and the PWM control voltage V_c between 0 and V_{rpp}.
  b. Set the load resistance R_o to 50Ω, which is equal to the value of the load resistance used on the **Discrete Buck Section** of the TI Power Electronics Board for NI ELVIS III.
  c. Set the frequency, amplitude and offset of the triangular carrier signal V_r at 100kHz, 1Vpp and 0.5V respectively.
  d. Set the DC magnitude of the control signal V_c at 0.5V.
  e. Run the simulation, watch and record the average output voltage while increasing the frequency of the triangular carrier signal in 100kHz steps, up to 1MHz.
     You should observe that the frequency does not influence the PWM modulator and the average output voltage.

- Measurements
  a. Follow the instructions provided in ***Section 4.1*** to setup the **Discrete Buck Section** of the TI Power Electronics Board for NI ELVIS III.
  b. Set the *Power Supply* voltage at 7V.
  c. Set the frequency, amplitude and offset of the *Function Generator* CH-1 (V_r) at 100kHz, 1Vpp and 0.5V respectively.
  d. Set the frequency, amplitude and offset of the *Function Generator* CH-2 (V_c) at 1Hz, 0Vpp and 0.5V respectively.
  e. Run the experiment, watch and record the average output voltage while increasing the frequency of the *Function Generator* CH-1 in 100kHz steps, up to 1MHz.

Due to delay times and other properties of the real PWM modulator and of MOSFET gate drivers, you may observe a change in the average output voltage as the frequency increases. Describe and discuss the differences you observe between simulations and measurements

6-2-2. Run the ***Lab1 – Linear Regulator in Open-Loop DC Operation***, and compare the efficiency performance of a linear regulator to the efficiency performance of the MOSFET half-bridge under similar input and output conditions. The MOSFET of in the Discrete Linear Regulator is the same component used in the half-bridge of the **Discrete Buck Section**.

6-4 Resources for learning more

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