ECEN 438/738 – Power Electronics Spring 2025

Lab 1: Linear Regulator in Open Loop

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The goal of this lab is to investigate the properties of a MOSFET in DC operation, when it works as a pass device in linear regulators. First, we review the equations describing the behavior of a MOSFET in DC operation, and discuss the impact of the gate-to-source voltage on the operating point. Next, we predict the MOSFET operating region and calculate the power losses and temperature under different conditions. Then, we simulate the MOSFET using its physical model. Finally, we perform lab experiments to estimate the real value of MOSFET parameters and compare their impact on the accuracy of theoretical and simulation predictions.

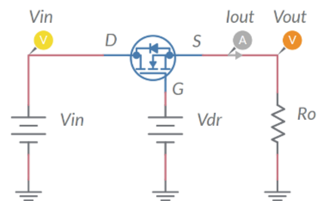

Figure 1-1. Linear Regulator

Learning Objectives

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

1. Given the parameters of a MOSFET, a source voltage and a load resistance, you will calculate the gate driver voltage required to achieve a desired output voltage, you will determine the MOSFET operating region and calculate its drain-to-source voltage and current, power losses and junction temperature, with specified units and accuracy, by applying the appropriate MOSFET equations
2. Given the parameters of a MOSFET, a source voltage, and a load resistance, you will determine the gate driver voltage required to achieve a desired output voltage by simulating the MOSFET operation, you will determine the MOSFET operating region and calculate its drain-to-source voltage and current, power losses and junction temperature, with specified units and accuracy, and you will determine the accuracy of theoretical predictions.
3. Given a real MOSFET, a DC power supply, a load resistor of given resistance, and a function generator, you will set experimentally the MOSFET gate driver voltage allowing to achieve a desired output voltage, you will record the measurement, with specified units and accuracy, you will compare the measured values with the simulations, and you will determine the accuracy of simulations.

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 MOSFET as a linear regulator. This important feature is utilized in a large variety of low-power applications, where a well regulated DC voltage is required.

1-2 The linear regulator concept

Figure 1-2 shows a circuit composed of a voltage generator, V_{in}, a load resistor, R_o, and a variable resistor, R_{var}.

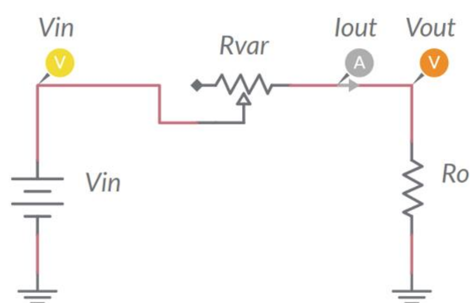

Figure 1-2. Resistive Voltage Divider

If the voltage V_{out} required by the load is lower than V_{in}, then the voltage drop across the variable resistor must equal the difference V_{in}-V_{out}. The value of the resistance R_{var} required to achieve the desired load voltage V_{out}, is given by Equation 1-1:

Equation 1-1

$$R_{\mathrm{var}} = \frac{V_{in} - V_{out}}{V_{out}} R_o = \frac{V_{in} - V_{out}}{I_{out}}$$

The resistance R_{var} depends on the input voltage V_{in}, and on the load current, I_{out}: it must be adjusted to maintain the output voltage regulated at the desired value V_{out}, when V_{in} and I_{out} are subjected to time variations. This happens in many practical applications, where the source voltage V_{in} can be affected by disturbances (e.g. automotive power electronics) and the load can require a variable power (e.g. power signal amplifiers).

1-3 MOSFET operating as linear regulator

Figure 1-3 shows the basic circuit schematic of a linear regulator, using an N-channel MOSFET as a “pass device”.

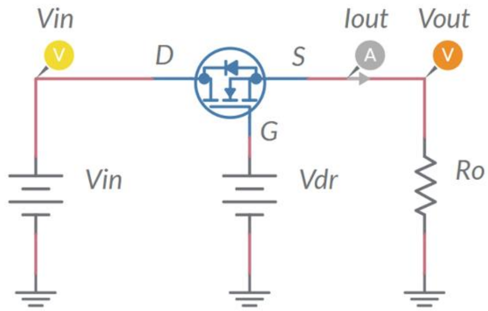

Figure 1-3. MOSFET Operating as Linear Regulator

The linear regulator uses the MOSFET capability to emulate a variable resistor, whose resistance is driven by the gate-to-source voltage applied between the gate (G) and the source (S). The output voltage V_{out} can be regulated at the desired value by adjusting the gate-to-source voltage. The circuit driving the MOSFET gate-to-source voltage works as a source, providing a voltage V_{dr}. The voltage V_{dr} is applied to the gate terminal G and yields a gate-to-source voltage $V_{GS} = V_G - V_{out} = V_{dr} - V_{out}$. Equations 1-2 (also called MOSFET output characteristics) describe the MOSFET drain-to-source current in DC operation, as function of the drain-to-source voltage and gate-to-source voltage:

Equations 1-2

$$\text{cut-off region:} \quad V_{GS} < V_{th} \Rightarrow \quad I_{DS} = 0$$

$$\text{saturation region:} \quad V_{GS} > V_{th}, \quad V_{DS} > V_{GS} - V_{th} \Rightarrow \quad I_{DS} = \frac{\beta}{2}(V_{GS} - V_{th})^2(1 + \lambda V_{DS})$$

$$\text{ohmic region:} \quad V_{GS} > V_{th}, \quad V_{DS} < V_{GS} - V_{th} \Rightarrow \quad I_{DS} = \frac{\beta}{2} V_{DS}[2(V_{GS} - V_{th}) - V_{DS}](1 + \lambda V_{DS})$$

V_{th} is the gate-to source threshold voltage, β is the trans-conductance coefficient, and λ is the channel-length modulation coefficient. Equations 1-2 highlight that, given the drain-to-source voltage V_{DS}, the current I_{DS} the MOSFET lets to pass from drain to source is determined by the gate-to-source voltage V_{GS}. The operating point of the MOSFET is determined by the combination of its own characteristics with the source and load parameters.

1-4 MOSFET DC operating point

The grey lines in Figure 1-4 are the plots of Equations 1-2, parameterized with respect to the gate-to-source voltage. The red line in Figure 1-4 is the locus of operating points of the MOSFET determined while varying the gate-to-source voltage, given the source voltage V_{in} and the load resistance R_{load}, while the green line is locus of the MOSFET DC operating points allowed by a given gate-to-source voltage V_{GS}^{*}.

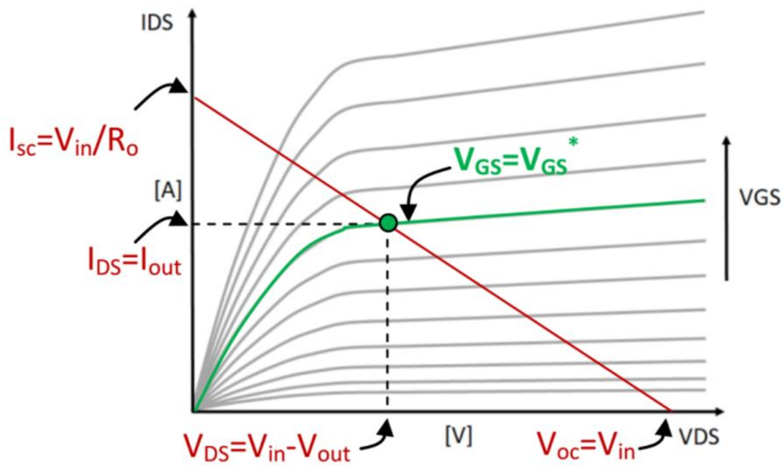

Figure 1-4. Determination of the MOSFET DC Operating Point.

The intersection of the red and green lines is the MOSFET DC operating point. It can be determined by means of the constraints given by Equations 1-3 to 1-5:

Equation 1-3
$$V_{DS} = V_{in} - V_{out}$$

Equation 1-4
$$V_{GS} = V_{dr} - V_{out}$$

Equation 1-5
$$I_{DS} = I_{out} = \frac{V_{out}}{R_o}$$

Combining Equations 1-2 to 1-5 allows determining the gate driver voltage V_{dr}, given the input voltage V_{in}, the load resistance R_o and the desired output voltage V_{out}. Neglecting the minor impact of the channel-length modulation coefficient λ in DC operation yields the simplified Equations 1-6 and 1-7:

saturation region *(the equations are valid if $V_{DS} > V_{GS} - V_{th} \Rightarrow V_{in} > V_{dr} - V_{th}$):*

Equation 1-6
$$V_{dr} = V_{th} + V_{out} + \sqrt{\frac{2V_{out}}{R_o \beta (1 + \lambda (V_{in} - V_{out}))}} \cong V_{th} + V_{out} + \sqrt{\frac{2V_{out}}{R_o \beta}}$$

ohmic region *(the equations are valid if* $V_{DS} < V_{GS} - V_{th} \Rightarrow V_{in} < V_{dr} - V_{th}$*):*

Equation 1-7

$$V_{dr} \cong V_{th} + \frac{V_{in} + V_{out}}{2} + \frac{V_{out}}{R_o \beta (V_{in} - V_{out})}$$

The gate driver voltage V_{dr} required to achieve the desired output voltage V_{out} is independent of the input voltage V_{in} when $V_{in} > V_{dr} - V_{th}$ (MOSFET operating in the saturation region), whereas it increases while the input voltage V_{in} decreases when $V_{in} < V_{dr} - V_{th}$ (MOSFET operating in the ohmic region). Equations 1-6 and 1-7 highlight that a MOSFET with a higher V_{th} requires a higher driver voltage V_{dr} to achieve the desired output voltage V_{out}. The minimum input voltage V_{inmin} allowing the output voltage regulation is determined by the gate driver voltage rating V_{drmax}. The difference $V_{inmin} - V_{out}$ is the “dropout voltage” of the linear regulator. *Low Dropout Regulators* (LDO) are characterized by a small dropout voltage.

1-5 MOSFET thermal properties

The MOSFET can operate at a maximum junction temperature rating T_{rating} of 150°C or 175°C, depending on its technology. Exceeding the maximum junction temperature may result in damage of the MOSFET and possible fault in the operation of the circuit where the MOSFET is used. The junction temperature depends on the MOSFET power loss, which can be calculated by means of Equation 1-8:

Equation 1-8

$$P_{loss} = V_{DS} I_{DS} = (V_{in} - V_{out}) \frac{V_{out}}{R_o}$$

Given the ambient temperature T_a, the MOSFET junction temperature T_j is given by Equation 1-9:

Equation 1-9

$$T_j = T_a + R_{\theta ja} P_{loss}$$

The coefficient $R_{\theta ja}$ is the thermal resistance of the MOSFET, determined by the package.

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 Given the source voltage and load resistance, how does the MOSFET drain-to-source **current change** as the gate driver voltage increases?

A. it increases
B. it decreases
C. it is not influenced

1-2 Given the source voltage and load resistance, how does the MOSFET drain-to-source **voltage change** as the gate driver voltage increases?

A. it increases
B. it decreases
C. it not influenced

1-3 Given the desired output voltage and load resistance, how does the required MOSFET gate driver voltage change while the input voltage decreases, if the MOSFET operates in the saturation region?

A. it increases
B. it decreases
C. it is not influenced

1-4 When does the MOSFET operate in the ohmic region as a linear regulator?

A. never
B. when the input voltage is much higher than the required output voltage
C. when the input voltage is a little higher than the required output voltage

1-5 Given the source voltage and load resistance, how does the MOSFET power loss change as the gate driver voltage increases?

A. increases
B. not influenced
C. non monotonic

2 Exercise

The Texas Instruments CSD15380F3 (http://www.ti.com/lit/ds/symlink/csd15380f3.pdf) N-channel MOSFET Q1 used in the **Discrete Linear Section** of the TI Power Electronics Board for NI ELVIS III has the following nominal parameters:

- V_{th} = 1.1V [the real value of V_{th} can range between 0.85V and 1.35]
- β = 0.24A/V^2 [the real value of β can range between 0.19V and 0.33]
- λ =0.02V^{-1} [the real value of λ can range between 0.01V and 0.05]
- $R_{\theta ja}$ = 255°C/W [the real value of $R_{\theta ja}$ is influenced by the device mounting]

Assume the following operating parameters:

- V_{in} = 7V
- R_o = 120Ω
- T_a = 30°C

2-1 Using the rules and equations provided in the **Theory and Background** section, calculate the gate driver voltage V_{dr} required to achieve the values of output voltage listed in column 1 of Table 2-1, determine the status of the MOSFET (OFF = cut-off, SAT = saturation, OHM = ohmic), calculate the drain-to-source voltage and current, the power loss and the junction temperature of the MOSFET, with three decimal digits (for the temperature use one decimal digit), and report the results in Table 2-1.

Table 1-1 Gate driver voltage required to achieve a desired output voltage, given the source voltage and load resistance

1	2	3	4	5	6	7
V_{out} [V]	status	V_{dr} [V]	V_{DS} [V]	I_{DS} [A]	P_{loss} [W]	T_j [°C]
1.5						
3.0						
4.5						
6.0						

3 Simulate

The simulations you will perform in this section allow you to analyze the impact of the gate driver voltage V_{dr} on the operating point of a MOSFET operating as a linear regulator. You will compare the results of the simulations with the results of calculations performed in the **Exercise** section, based on the simplified Equations 1-6 - 1-9, to verify the theoretical prediction and evaluate the impact of MOSFET parameters on the DC operating point.

3.1 Instructions

1. Open *Lab1 – MOSFET DC operation* from this file path:
   https://www.multisim.com/content/vuVttWyHxrRuPfki7F33Ad/lab-1-linear-regulator-open-loop-dc-operation/

   The circuit schematic for the analysis of MOSFET DC operating points is shown in Figure 3-1. The MOSFET is modeled by means of an *Analog Behavioral Modeling* current source (*ABM* current source). The *ABM* model implements the MOSFET Equations 1-2 provided in the **Theory and Background** section. The MOSFET parameters are set by means of the voltage sources *Vth*, *beta* and *lam* at the values used in the **Exercise** section.

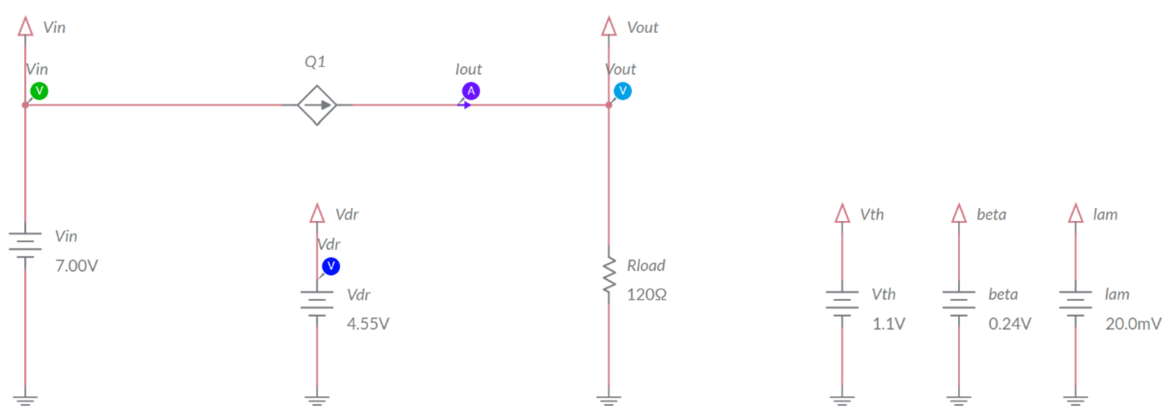

Figure 3-1. Multisim Live Circuit Schematic for the Analysis of a Linear Regulator in Open Loop DC Operation

2. Select the *Interactive* simulation option and the *Schematic* visualization option.
3. Set the gate driver voltage V_{dr} at zero.
4. Run the simulation and increase the gate driver voltage (V_{dr}) until the number shown by the output voltage probe (V_{out}) equals the value of the output voltage indicated in the first column-first row of Table 3-1, with three decimal digits.
5. Record the value of the gate driver voltage in the second column of Table 3-1.

6. Repeat the simulation for all the values of the output voltage V_{out} listed in column 1 of Table 3-1.
7. Import in column 3 of table 3-1 the values of gate driver voltage reported in column 2 of Table 2-1 of **Exercise** section.
8. Calculate the % error ($V_{dr,cal}$-$V_{dr,sim}$)/$V_{dr,sim}$ x 100 between the values of the gate driver voltage V_{dr} obtained with calculations and simulations.
9. Calculate the power loss and the junction temperature of the MOSFET.
10. Calculate the % efficiency $\eta = P_{out}/P_{in}$ x 100= V_{out}/V_{in} x 100.

Table 3-1 Gate driver voltage required to achieve a desired output voltage, given the source voltage and load resistance

1	2	3	4	5	6	7
V_{out} [V]	$V_{dr,sim}$ [V]	$V_{dr,cal}$ [V] from column 2 of Table 2-2	V_{dr} error [%]	P_{loss} [W]	T_j [°C]	η [%]
1.5						
3.0						
4.5						
6.0						

3-1 Does the maximum power loss correspond to the minimum efficiency?

A. yes
B. no
Please provide your comment ____

____

3-2 What is the maximum V_{dr} % error between calculations and simulations?

A. max % error <1%
B. 1% < max % error < 10%
C. max % error >10%

3-3 Do you identify a trend in the V_{dr} error values vs the output voltage V_{out}?

A. yes
B. no
Please provide your comment ____

3-4 What is the possible origin of the error between V_{dr} calculations and simulations?

Troubleshooting tips:

- If you get an error greater than 10% between simulation and calculation results, check the values of source voltage, load resistance and MOSFET parameters.
- If the simulation does not converge and you get some error message, reload *Lab1 – Linear Regulator in Open Loop DC Operation* from this file path: https://www.multisim.com/content/vuVttWyHxrRuPfki7F33Ad/lab-1-linear-regulator-open-loop-dc-operation/ and restart the simulation following the relevant instructions.

4 Implement

The **Discrete Linear Section** of the TI Power Electronics Board for NI ELVIS III shown in Figure 4-1 allows performing experiments on MOSFET DC Operation as linear regulator. The jumpers and test points used to setup the tests and measure the signals of interest are highlighted. The experiments you perform in this section allow you to observe the behavior of a real MOSFET in DC operation, to verify the effect of the gate driver voltage on the MOSFET status and operating condition. You will compare the experimental measurements with the results of simulations. Next, you will verify the compliance of the MOSFET simulation model with the real MOSFET behavior. Finally, you will determine possible adjustments of MOSFET model parameters to improve accuracy of simulations. The MOSFET Q24 of the linear regulator is a Texas Instruments CSD15380F3 (http://www.ti.com/lit/ds/symlink/csd15380f3.pdf). [**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]

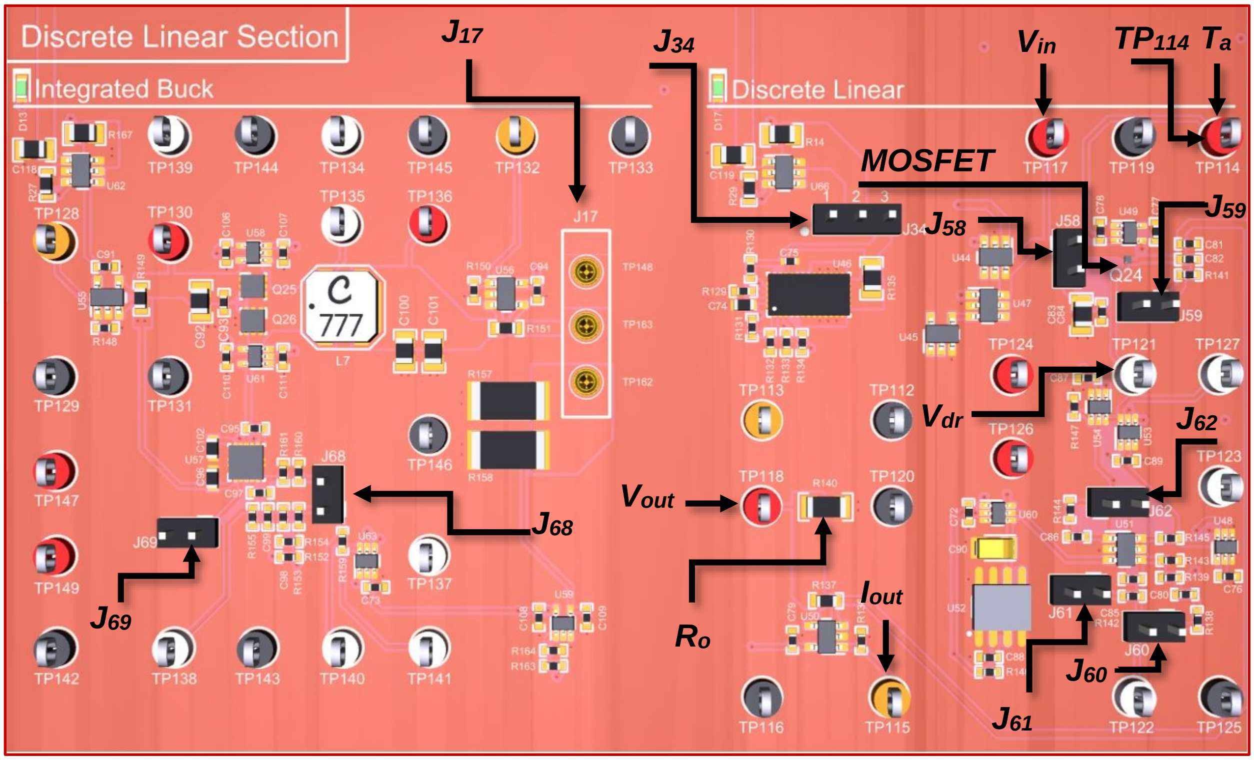

Figure 4-1. TI Power Electronics Board for NI ELVIS III - Discrete Linear Section Used for the Analysis of a Linear Regulator in Open Loop DC Operation.

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 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 *Lab1 – Linear Regulator in Open Loop DC Operation*.
5. Configure the jumpers of the board as indicated in Table 4-1.
6. Configure and connect the instruments as indicated in Tables 4-2 and 4-3.

Table 4-1 Jumpers setup

J17	J34	J58	J59	J60	J61	J62	J68	J69
short TP162-TP163	short 2-3	open	short	short	short	short	short	short

Table 4-2 Instruments Configuration and setup

Power Supply	*Channel "+"*: Static, 7.00V, *Channel "-"*: Inactive			
Oscilloscope	*Trigger*: Immediate	*Horizontal*: 100us/div	*Acquisition*: average	*Measurements*: show
	Channel 1: ON • DC coupling • 1V/div • offset -4.0V • position -4.0V	*Channel 2*: ON • DC coupling • 1V/div • offset -4.0V • position -4.0V	*Channel 3*: ON • DC coupling • 1V/div • offset -4.0V • position -4.0V	*Channel 4*: OFF
Function Generator	*Channel 1*: Inactive *Channel 2*: Sine, Frequency 1Hz, Amplitude 0.00Vpp, DC offset 0.00V			
Digital Multimeter	*Measurement mode*: DC voltage; *Range*: Automatic			

Table 4-3 Instruments Connections

Power Supply	connect to red and black banana connectors
Oscilloscope	connect Ch-1 to TP117 (V_{in}), connect Ch-2 to TP118 (V_{out}) connect Ch-3 to TP121 (V_{dr})
Function Generator	connect Ch-2 to FGEN2 BNC connector ($\rightarrow$TP121 = Discrete Linear V_{dr})
Digital Multimeter	connect Voltage input to TP115 (I_{out})

7. Run *Power Supply*, *Function Generator*, *Oscilloscope* and *Digital Multimeter*.
8. Adjust the *Power Supply* voltage until the RMS measurement of *Oscilloscope* Ch-1 (V_{in}) equals 7.00V [**Note:** in this experiment, use Volts, Ampères and Watts in voltage, current and power measurements and calculations, respectively, with three decimal digits].
9. Increase the DC offset of the *Function Generator* Ch-2 (V_{dr}) until the RMS measurement of the *Oscilloscope* Ch-2 (V_{out}) equals the value of the output voltage indicated in the first column-first row of Table 4-4. [**Note:** the maximum allowed value of gate driver voltage V_{dr} is $\boldsymbol{V_{dr,max}}$ **= 6.5V**]
10. Read the RMS measurement of the *Oscilloscope* Ch-3 (V_{dr}) and the *Digital Multimeter* measurement (I_{out}), calculate the input power $P_{in} = V_{in} \times I_{out}$, and record the values in columns 2, 5 and 6 of Table 4-4, respectively.
11. Calculate the output power $P_{out} = V_{out} \times I_{out}$, and the % efficiency $\eta = P_{out}/P_{in} \times 100$, with one decimal digit, and report the result in columns 7 and 8 of Table 4-4, respectively.

12. Connect the *Digital Multimeter* to Test Point TP114, read the DC voltage measurement V_{TP114} in Volts, calculate the ambient temperature according to the formula T_a = (V_{TP114} – 0.5V) x 100, calculate the MOSFET junction temperature according to the formula $T_j = T_a + (P_{in} – P_{out})R_{\theta ja}$, and report the result in column 9.
13. Repeat the measurements for all the values of the output voltage V_{out} listed in column 1 of Table 4-4.
14. Stop *Power Supply*, *Function Generator*, *Oscilloscope* and *Digital Multimeter*.
15. Import in column 3 of Table 4-4 the values of voltage V_{dr_sim} reported in column 2 of Table 3-1 of **Simulate** section.
16. Calculate the % error $(V_{dr,sim}-V_{dr,meas})/V_{dr,meas}$ x 100 between the values of the voltage V_{dr} obtained with simulations and measurements.

Table 4-4 DC operating point of the MOSFET, given the source voltage, load resistance and gate driver voltage

1	2	3	4	5	6	7	8	9
V_{out} [V]	$V_{dr,meas}$ [V]	$V_{dr.sim}$ [V] from column 2 of Tab 3-2	V_{dr} error [%]	I_{out} [A]	P_{in} [W]	P_{out} [W]	eff [%]	T_j [°C]
1.50								
3.00								
4.50								
6.00								

4-1 What is the maximum V_{dr} % error between simulations and measurements?

A. max % error <1%

B. 1% < max % error < 10%

C. max % error >10%

4-2 What is the possible origin of the error between V_{dr} calculations and simulations?

____

4-3 Did you to achieve the required output voltage with a gate driver voltage lower than the maximum allowed value of 6.5V?

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

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Troubleshooting tips:

- If the MOSFET does not work, or if the error between simulation and measurement is greater than 20%, verify the correct setup and connections of instruments, based on directions provided in Tables 4-1 and 4-2, and restart the experiment.

5 Analyze

5-1 Graph the values of voltage V_{dr} collected in columns 2 and 3 of Table 4-4 as a function of the required voltage V_{out}, including a legend that indicates which line style corresponds to which series (simulations, measurements).

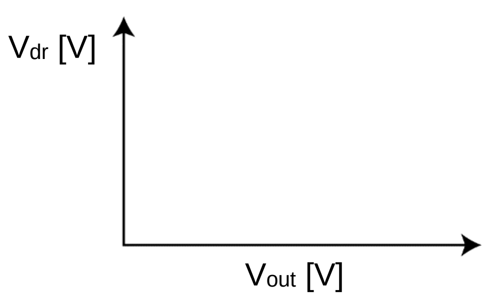

Figure 5-1 Simulated and Measured Values of Output Voltage V_{out} versus the Gate Driver Voltage V_{dr}.

5-2 Are the V_{dr} error values positive or negative?

A. always positive
B. always negative
C. either sign
Please provide your comments: ______________________________________

____

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____

5-3 Do you see a trend in the V_{dr} error values vs the output voltage V_{out}?

A. increasing
B. decreasing
C. no precise trend
Please provide your comments: ______________________________________

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____

5-4 Based on your observations and on the MOSFET properties discussed in the **Theory and Background** section, what parameter would you modify in the MOSFET model to reduce the error between measurements and simulations? How and why?

A. V_{th}: ____

B. β: ____

C. λ: ____

5-5 Re-run the simulation by changing the parameters of MOSFET model, based on your answers to Question 5-5, and verify your predictions. Are the new simulation results closer to experimental ones? Do you infer a rule or a procedure to obtain the parameters of a MOSFET from experimental measurements?

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6 Conclusion

6-1 Summary

Write a summary of what you learned and observed about the impact of MOSFET gate driver voltage and physical parameters on the linear regulator open loop DC operation. Explain why it is important to predict correctly the gate driver voltage value needed to achieve a desired value of the output voltage, and how the MOSFET parameters influence the value of gate driver voltage.

6-2 Expansion Activities

6-2-1. Investigate how the source voltage V_{in} influences the MOSFET operation, by determining the transition from saturation region to ohmic region. The investigation can be performed by means of simulations and experiments. In both cases, set the source voltage V_{in} at a given value (not exceeding 10V) and find the gate driver voltage V_{dr} that determines an output voltage $V_{out} = V_{in}/2$. Then, decrease the source voltage V_{in} in 100mV steps, while observing the output voltage V_{out}. You will observe no change in the output voltage until the input voltage reaches a certain value, below which you will see the output voltage to decrease. The change of behavior of the MOSFET is determined by the transition from the saturation to the ohmic region.

6-2-2. Repeat the Simulation 2 discussed in the **Simulate** section, by changing the voltage of sources *Vth*, *beta* and *lam* in the ranges indicated in Table 6-1, to investigate the sensitivity of the MOSFET DC operation point with respect to its model parameters.

Table 6-1 Gate driver voltage required to achieve a desired output voltage, given the source voltage and load resistance

min V_{th} [V]	max V_{th} [V]	min beta [S]	max beta [S]	min lam [V^{-1}]	max lam [V^{-1}]
0.85	1.35	0.19	0.33	0.01	0.05

6-3 Resources for learning more

- This document provides the fundamentals of linear regulators:

Linear Regulators: Theory of Operation and Compensation, http://www.ti.com/lit/an/snva020b/snva020b.pdf