EXPERIMENT 2

Power MOSFET Motor Driver

2.1 Application

Circuity used in high power devices such as power supplies or motors often use low power signals generated from sensitive electronics to control the system. Transistors are commonly used to achieve this; however, because of the high power nature of the system, one must give special attention to the power consumed by the transistor. In this experiment, we will use a motor to demonstrate how using a metal-oxide-semiconductor field-effect transistor (MOSFET) as a switch can enable a low current signal to control a high current signal with very little power wasted.

2.2 Linear operation

The I–V characteristics of Figure 2.1 shows the linear region of operation for MOSFETs; Within this region, MOSFETs act almost like resistors in which the current i_D is proportional to the voltage v_{DS} across the MOSFETs, as shown in equation (2.1). This resistance is called the on-resistance $R_{DS(on)}$. The effective resistance of the device is controlled by the v_{GS} applied to the transistor.

$$i_D = k_n\left((v_{GS} - V_{th})v_{DS} - \frac{1}{2}v_{DS}^2\right) \tag{2.1}$$

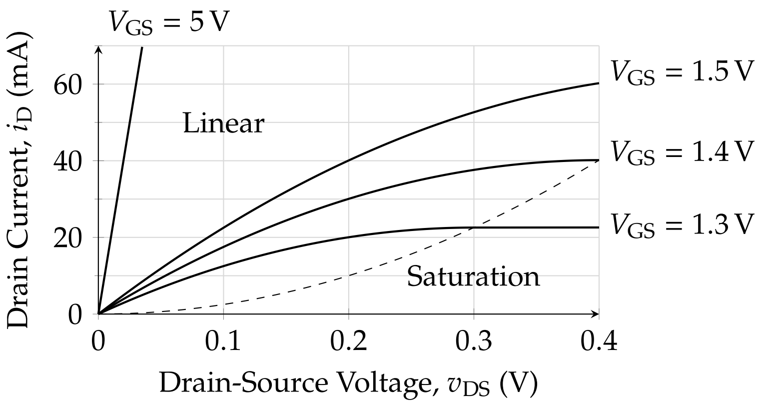

Figure 2.1: Linear region of operation for an n-channel enhancement mode MOSFET with $k_n = 0.5\,A\,V^{-2}$ and $V_{th} = 1\,V$.

The on-resistance is an important parameter for determining the power handling capability of a MOSFET, and values in the tens of milliohms or lower have been achieved in commercially available transistors. Mathematically, $R_{DS(on)}$ is defined by the inverse slope of the i_D versus v_{DS} curve for a specific v_{GS}, so it can be calculated as shown in equation (2.2).

$$R_{DS} = \left[\left.\frac{\partial i_d}{\partial v_{DS}}\right|_{v_{GS}=\text{constant}}\right]^{-1} \tag{2.2}$$

$R_{DS(on)}$ for a specific v_{GS} may be estimated from the MOSFETs output characteristics using equation (2.2). For example, in figure 2.1, $R_{DS(on)}$ may be estimated for $v_{GS} = 1.5\,V$ over the v_{DS} range of 0 V to 0.2 V by the simple ratio of $^{0.2\,V}/_{40\,mA} \approx 5\,\Omega$. This means that the transistor can be modelled as a $5\,\Omega$ resistor between the drain and source when the current is below 40 mA and $v_{GS} = 1.5\,V$. As v_{GS} increases, the slope of the

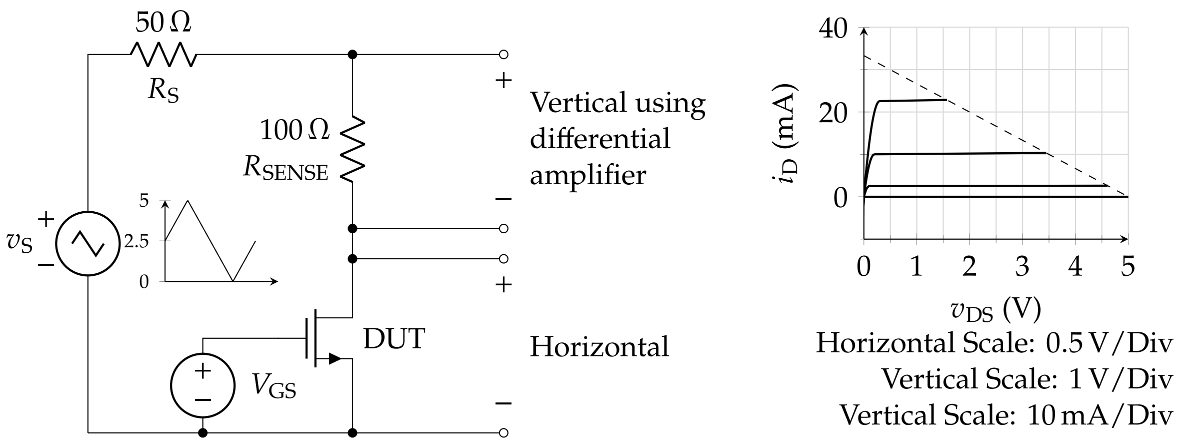

Figure 2.2: A test set to obtain typical output characteristics of a MOSFET.

i_D versus v_{DS} curve continues to increase, so the effective $R_{DS(on)}$ of the device decreases. If we look at the curve for $v_{GS} = 5\,\mathrm{V}$ in figure 2.1, we can estimate the on resistance as $^{0.03\,\mathrm{V}}/_{60\,\mathrm{mA}} \approx 0.5\,\Omega$.

2.3 A test set to obtain complete output characteristics

In order to obtain the complete output characteristics of a MOSFET, it will be helpful to use a typical set circuit as shown in figure 2.2. The test circuit of figure 2.2 consists of two loops:

Drain-source loop. v_S sweeps the drain supply from 0 V to 5 V. The 50 Ω resistor is internal to the function generator and limits the output current.[1] R_{SENSE} can be used to measure the current flowing into the transistor.

[1] The AD2 does not have this 50 Ω resistor, but the ADALM2k and benchtop equipment do

Gate loop. v_{GS} adjusts the gate voltage. To obtain the solid characteristic curve shown in figure 2.2, the gate voltage is set to a desired value and V_{DD} is automatically swept from 0 V to a peak voltage of 5 V. The dashed curves represent characteristics obtained using other, appropriately spaced values of v_{GS}.

2.4 Driving high current loads with MOSFETs

The MOSFET can be quickly turned on and off to drive a high current load beyond the capabilities of the device generating the control signal. This technique is commonly used in electromechanical devices like motors, solenoids, and relays, but it is also useful for controlling the brightness of LEDs.

2.4.1 Motor control

There are two common methods for controlling a motor. The most obvious method is to adjust the voltage applied to the motor. As the voltage decreases, the motor speed will also decrease. Unfortunately, this method typically is either inefficient or difficult to implement. The more common method is called pulse width modulation (PWM).

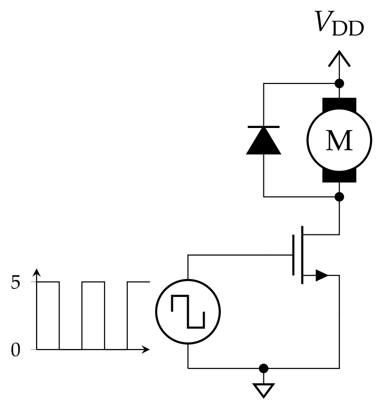

Figure 2.3: Circuit for PWM motor control

Figure 2.3 shows a simple method for PWM motor control. In this case, a periodic pulse with certain duty cycle is sent to turn the MOSFET on and off; that is, we use the MOSFET as a switch. In the low-side configuration, the power consumption of the MOSFET can be approximated by the following equation:

$$P_{\text{mosfet}} = \alpha \cdot i_{\text{D}} \cdot v_{\text{DS}}^{\text{on}} + (1 - \alpha) \cdot i_{\text{D}} \cdot v_{\text{DS}}^{\text{off}} \tag{2.3}$$

where α is the duty cycle of the pulse.

Duty cycle is fraction of a period in which the signal is active.

When the MOSFET is off, there should be effectively no current, so we can rewrite equation (2.3) into:

$$P_{\text{mosfet}} = \alpha \cdot i_{\text{D}} \cdot v_{\text{DS}}^{\text{on}} \tag{2.4}$$

As a result, the power consumption of the MOSFET solely relies on the energy consumed when it is on.

2.5 DC motor with quadrature encoder

Driving a DC motor with a DC power supply is useful in industrial applications like conveyors, turntables and many others. Sometimes it would be helpful if one could know the direction and the speed of the motor for monitoring and controlling purposes. A motor encoder was invented for this purpose. Specifically, a quadrature encoder is utilized to sense the direction of motor movement as well as its speed.

The sensor inside a quandrature encoder emits two square or sine waves. The two waveforms are 90° out of phase but with identical frequencies. It is possible to determine the direction of the motor by observing the phase relationship between two channels.

The motor speed is related to the motor's gear ratio, pulses per revolution, and encoder waveform's frequency. You can calculate the motor speed in terms of RPM using the following formula:

$$\mathrm{RPM} = \frac{60f}{p \cdot r} \tag{2.5}$$

where f is the encoder output frequency. p is pulse per revolution of the motor and r is the gear ratio of the gearbox attached to the motor.

2.6 Prelab

Task 2.6.1: Prelab activities

1. Estimate $R_{DS(on)}$ for the transistor with output characteristics given in figure 2.1 when $i_D = 30\,\text{mA}$ and $v_{GS} = 1.4\,\text{V}$.
2. Which value of v_{GS} in figure 2.1 has the lowest $R_{DS(on)}$ for all currents?
3. Use equation (2.2) and equation (2.1) to derive the R_{DS} value for a transistor in the linear region in terms of v_{GS}, v_{DS}, V_{th} and k_n. If we assume that v_{DS} is very small, then what is the simplified equation for R_{DS}?
4. For the rectangular wave shown in figure 2.4, 5 V will be defined to be the operating state. What is the duty cycle (%) of the wave?

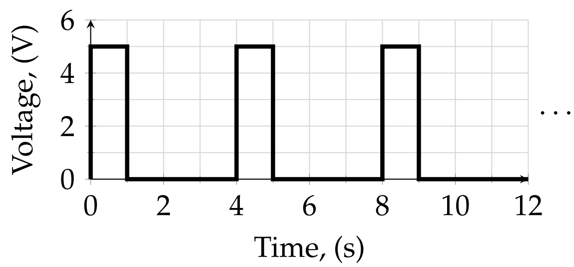

Figure 2.4: Example duty cycle waveform.

5. Review the datasheets for the LMC555 [1] and RFD3055LE [2]. What is the maximum continuous current that can be controlled by the *output* of each device? Use the absolute maximum ratings. Treat the drain current as the output of the RFD3055LE.

2.7 Tasks

Task 2.7.1: RFD3055LE output characteristics

1. *Select* R_{SENSE} for the test set in figure 2.2 to limit the worst case output current to 30 mA. The in lab function generator has a 50 ohm output impedance. The Analog Discovery 2 has a less than 1 ohm output impedance.
2. *Construct* the test set from figure 2.2 using the R_{SENSE} value calculated in step 1. Note that the diff amp circuit is built into the AD2. A prebuilt diffamp circuit is provided in lab. You will use the prebuilt diff amp circuit in lab or the differential inputs when using the AD2 device to measure measure the voltage across R_{SENSE}.
3. *Configure* the oscilloscope to use XY mode and plot the I–V characteristic of the RFD3055LE transistor. On the in lab equipment, use persistence to capture one curve in the cut-off region, one curve in the linear region and two curves in the saturation region. On the AD2, capture the 4 curves as separate screenshots.
4. *Label* the v_{GS} used for each curve.
5. *Estimate* the power consumed by the transistor for each measured curve at the largest v_{DS} by finding the points using the oscilloscope cursors. *Describe* the relationship between the power dissipation and transistor's mode of operation.
6. *Set* $V_{\text{GS}} = 5\,\text{V}$ then *capture* an oscilloscope screenshot showing the measurement. Use the results to estimate $R_{\text{DS(on)}}$ in the linear region of operation.
7. *Compare* the computed $R_{\text{DS(on)}}$ with the RFD3055LE datasheet $R_{\text{DS(on)}}$ value.

Task 2.7.2: PWM speed control with MOSFET switch

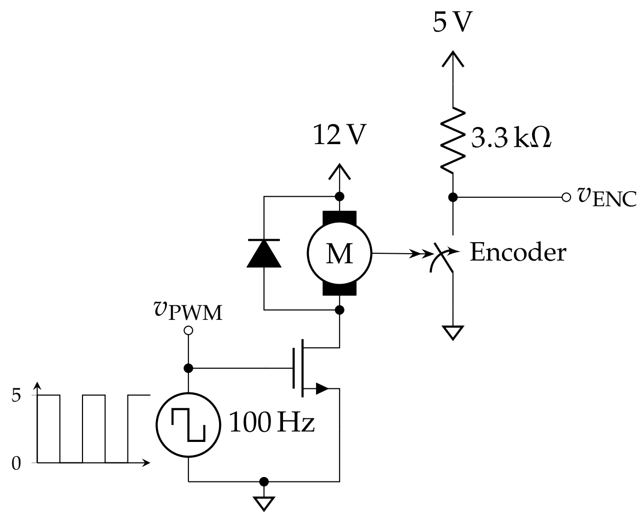

Figure 2.5: PWM motor speed controller.

1. *Construct* the circuit in figure 2.5. Use either output of the quadrature encoder for v_{ENC}. Use the 1N5819 diode and RFD3055LE MOSFET.
2. *Configure* the function generator to output a 100 Hz 0 V to 5 V square wave with a duty cycle of 50%.
3. *Capture* an oscilloscope screenshot showing v_{PWM} and v_{ENC}.
4. *Adjust* the function generator duty cycle from 10% to 90%. For each step, *Record* the motor RPM, the encoder frequency, and the average i_{D} reported by the power supply.
5. *Compute* the total power consumed by the circuit for each step.
6. *Plot* the control duty cycle versus the motor RPM and *describe* the relationship between them.

Task 2.7.3: LMC555 based PWM generator

In this task, we will create a circuit that can efficiently control the speed of a motor. Note that any load on the motor will still change the speed as this is open loop control. We will explore controls more in experiment 11.

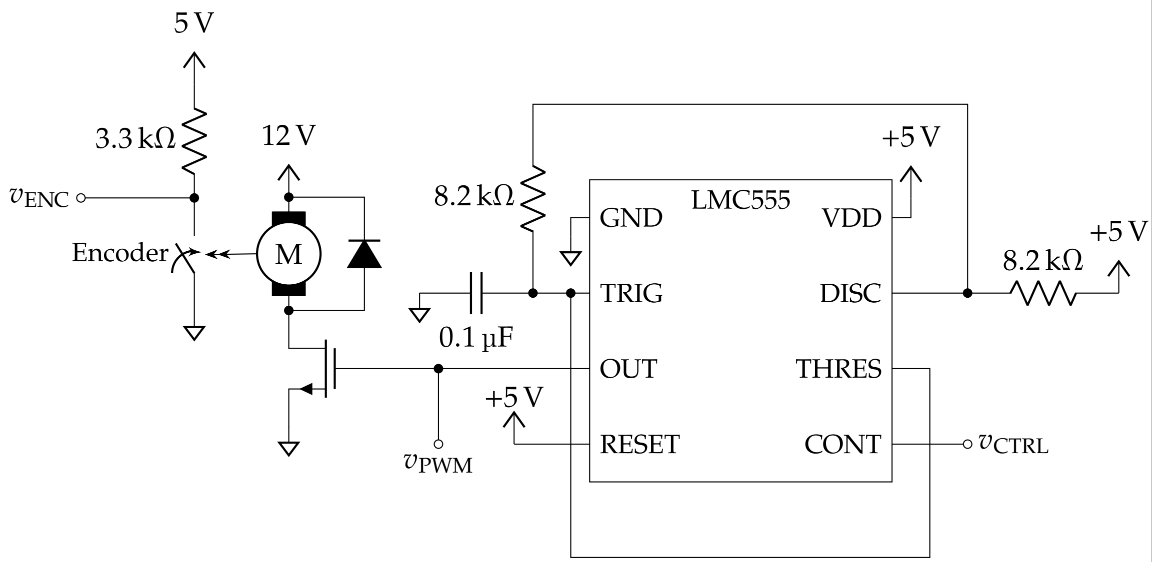

Figure 2.6: PWM Modulation Circuit for Motor Speed Control

1. *Construct* the circuit in figure 11.7. Use the 1N5819 for the diode and the RFD3055LE for the NMOS.
2. *Connect* v_{CTRL} to the function generator and configure the function generator to output DC.
3. *Setup* the oscilloscope to measure v_{PWM} and v_{ENC}.
4. *Adjust* v_{CTRL} from 0 V to 5 V and record the duty cycle of v_{PWM} and the speed of the motor at each step.
5. *Develop* a model for the relationship between v_{CTRL} and the speed of the motor.
6. *Replace* the function generator output with a potentiometer circuit that can adjust v_{CTRL} from 0 V to 5 V. Verify that your circuit is able to control the speed of the motor over its full range.

2.8 References

[1] *LMC555 CMOS timer*, LMC555, SNAS558M, Texas Instruments, Jul. 2016. [Online]. Available: `http://www.ti.com/lit/ds/symlink/lmc555.pdf`.

[2] *RFD3055LE, RFD3055LESM n-channel log level power MOSFET*, RFD3055LE, Rev C0, Fairchild Semiconductor, Sep. 2013. [Online]. Available: `https://www.onsemi.com/pub/Collateral/RFD3055LESM-D.pdf`.