Power transistors

In this lab, we look at some applications where larger transistors are used to deliver higher currents.

Op amps with feedback are excellent for providing voltage gain or regulation. Logic gates provide reliable high and low voltages for switching applications. But standard op amps and logic gates are unable to deliver large power to a load because they both have inherent output current limits. Whenever a low-power amp or gate needs to drive a high-current load (speakers, relay coils, motors, etc.), an "output stage" is needed to boost the current. Output stages can sometimes be implemented with one or a few power transistors, either BJTs or MOSFETs. A power transistor is fundamentally the same as the smaller transistors used in op amps or logic gates, but they are sized significantly bigger to handle more current and their packages may have heat sinks to facilitate cooling. The circuits in these exercises use the MJE180 (*npn*) and MJE170 (*pnp*) medium power BJTs and the IRF540 power MOSFET from the EE230 lab kits.

Prior to Lab

Look over the data sheets for the various transistors. Pay particular attention to the pin arrangements.

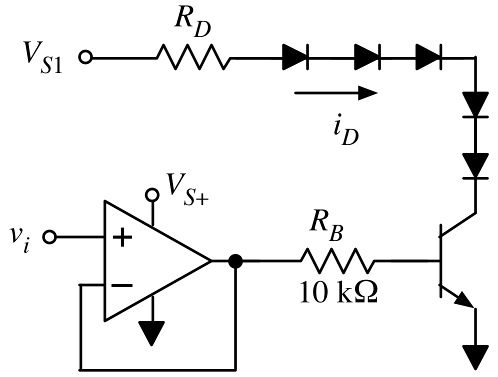
Caution!

When working with higher currents, the components dissipating that extra energy might get hot. Make sure that any resistors used as loads are adequately sized. The 2-W, 100-Ω resistor from the EE201 kit gets a workout in this lab. (If the high-power resistor is missing from your kit, you can probably can combine quarter-watt resistors to make an equivalent resistance that handle 1 or watts.) Also, when setting up the circuits, adjust voltage levels slowly and check continuously for components that are becoming hot.

A. Transistors as switches

There are many applications where a digital output (from a comparator or a micro-controller) must switch a high current load. A transistor can provide the necessary interface.

For example, an op amp will not be able to drive 100 mA of current through a series string of LEDs — the total voltage across the LEDs is probably too big and the current is definitely too big.



A circuit shown at right shows a simple way to power a string of LEDs. The unity-gain amp provides the base voltage to control the BJT switch, which in turn provides the current for the LEDs.

To build the circuit, use an LMC660 op amp with a single 5-V supply. (V_{S1} for diodes and V_{S+} for the op-amp supply should be separate supplies). R_D is the diode current-limiting resistor. Use the 2-W100-Ω resistor or make a 1-W 100-Ω combo using four quarter-watt 100-Ω resistors. You can use a random assortment of LEDs. (If you are more pedantic, you can use 5 of one color if you have them.) Depending on the LEDs used, the total voltage required to turn all the LEDs might range from 5 V to 15 V. Use an MJE180 *npn* BJT for the switch.

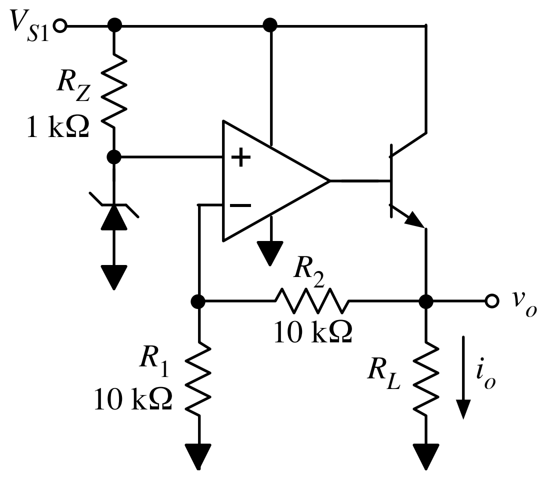
- Set v_i to 5 V, which should turn on the transistor. Then increase V_{S1} until the LED current is about 100 mA — the LEDs should be shining brightly.
- Confirm the operation of the switch by alternately setting the input voltage to 0 V and 5 V. Measure the various voltages and currents (v_{BE}, v_{CE}, i_D, the total voltage across the diodes) when the switch is “on”.
- Use the function generator in *pulse-width modulation* (PWM) mode to generate a PWM signal that switches between 0 and 5 V at a frequency of 500 Hz. Adjust the PWM duty cycle from 0% to 100% and observe the changes in the apparent LED output.
- Replace the BJT and R_B with a the IRF540 MOSFET and repeat the measurements and observations.
- Optional challenge: Use the MJE170 *pnp* transistor as the switch. Recall that it should be at the top (emitter up!) and it will turn on when the input goes low. Repeat the measurements and observations.
- Optional challenge: If you have an Arduino (or similar) and know how to program it, use it to provide the high and low inputs and the PWM signal to the op amp.

B. Voltage regulator

In class, we discussed using a Zener diode and a non-inverting amplifier to make a voltage regulator. At the time, we noted that the output power would be limited because of the current limit of a typical op amp. To make a better regulator, we should use a transistor to boost the current. The output of the op amp will control the transistor and feedback will continue to serve as the regulating mechanism.

The circuit at right is a basic10-V voltage regulator. To build it, use an LMC660 wired up to work off a single power supply. Use one of the Keysight bench supplies set to +14 V for V_{S1}. Use the 1N7433 Zener diode (5.1 V breakdown) as the reference. Use the MJE180 npn BJT as the *pass* transistor. Use the 2-W 100-Ω resistor as the load. The expected output voltage is

$$v_o = V_Z\left(1 + \frac{R_2}{R_1}\right) = 10.2\,\text{V}.$$



- Build the circuit and measure all of the relevant voltages and currents to confirm basic operation.
- Check the performance by varying V_{S1}. First, increase it to 16 V, and measure the voltage across the load. (Be careful — 16 V is upper limit for the

LMC600!) Then decrease V_{S1} to 12 V, and measure the output voltage again.

Any variation in the output voltage can be described in terms of *line regulation,* which is defined as the change in output voltage divided by the change in the supply voltage, $\Delta v_o / \Delta V_{S1}$. The ideal value for line regulation should be zero. Using the above measurements, calculate the line regulation for this circuit.

- Check the performance by varying the load current. Remove the 100-Ω load resistor and replace it with two 470-Ω resistors in parallel (= 235 Ω). Again, measure the change in the output voltage. Remove the 470-Ω resistors and replace them with two of the high-power 100-Ω resistors in parallel, creating a 50-Ω load. (Or try adding four 470-Ω resistors in parallel with the 100-Ω resistor to makes 54-Ω load. The five-resistor combo combination should be able to handle the power.) Measure the output voltage again.

  Any change in output voltage can be described in terms of *load regulation,* which is defined as the change in the output voltage divided by the change in the load current, $\Delta v_o / \Delta i_o$. The ideal value would be 0 Ω. Using your measurement, calculate the load regulation for this circuit.

- Next, check the performance by varying the current through Zener, which may change the reference voltage slightly. (There is no name for this variation.) Change R_Z to a 470-Ω resistor — approximately doubling the Zener current. Carefully measure the voltage across the Zener and the corresponding output voltage. Then change R_Z to a 2.2 kΩ resistor — approximately 50% of the original current — and measure the Zener and output voltages again. Any changes in output voltage would be indicative of the Zener being a "less than ideal" reference. Higher performance regulators use a better voltage reference circuit known as a band-gap reference — see EE 333 or EE 435.

- Finally, replace the BJT with the IRF540 NMOS — it will also work as a pass transistor. Check out its performance by repeating some of the measurements outlined above.

3. Class B amp[1]

The classic application of a Class B amp is provide current to drive a speaker in an audio system. Op-amps can provide voltage gain very nicely, but a typical loud speaker uses a coil having a resistance of either 4 Ω or 8 Ω. That low resistance will cause the op-amp to hit its output current limit very quickly. Once again, transistors are added between the op-amp and the load to provide the necessary current. In the steps below, we will build our way towards an implementation of a simple Class B amp. As a bonus, we will get yet another lesson in the power and utility of feedback.

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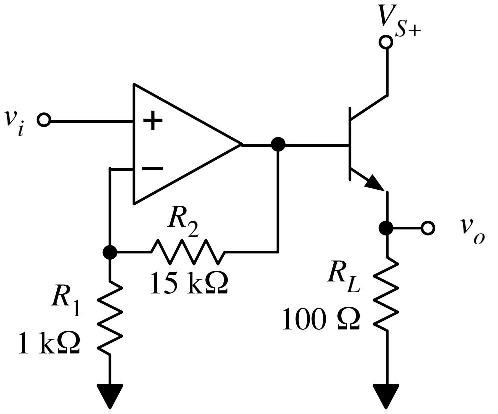
[1] There is a whole range of output amplifier classes: A, B, AB, C, D, and others. The distinctions are mainly based on efficiency of the output stage. It is useful to study the general features of output amps, but we will save that for another venue (EE 333 or EE 435). We can understand the basic features of a Class B amp by starting with the basic operating properties of BJTs and working our way towards the final circuit configuration. Learning how to calculate efficiency and other operational details can be done later.

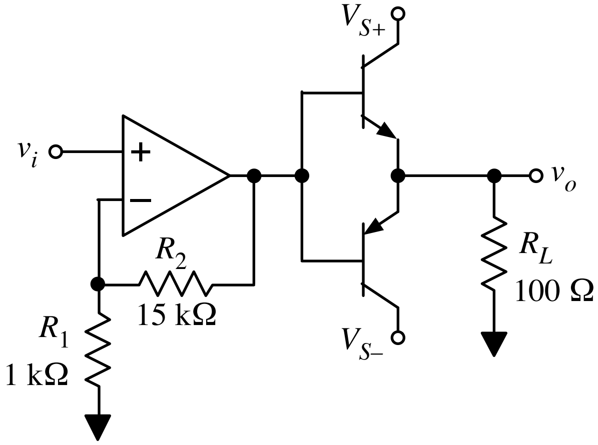
- Start by building a simple non-inverting amp with a gain of 16. Use one of amps on the TL082 chip. Use V_{S+} = 15 V and V_{S-} = –15 V for the power supplies. Check the operation by applying a 0.5-V_{RMS}, 1-kHz sinusoid at the input — obviously, the output should be a sine wave with an amplitude of 8 V_{RMS}. Take an oscilloscope trace to confirm the operation. (If the output is clipping, reduce the input amplitude until the the output is clean.)

- Attach the 2-W, 100-Ω resistor as a load. The amp current limit will probably clip the peaks of the the output sinusoid. Take an oscilloscope trace to show the distortion.

- Add an *npn* BJT (MJE180) to the output as shown. Since the BJT has current gain, it can easily provide the necessary current at the positive peaks of the sinusoid. The op amp now needs to provide only the relatively modest base current. Unfortunately, the *npn* turns on only when the op amp output voltage is greater than 0.7 V. Even though there is plenty of current to hit the peaks, the sinusoid has been rectified. Half of the signal is missing! Take a trace of the badly distorted output.



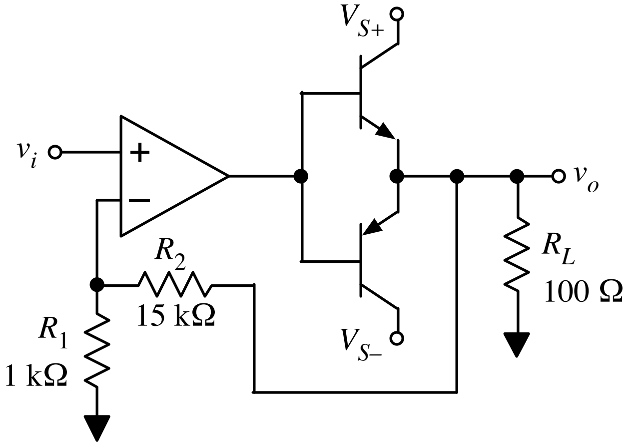
- Next add a *pnp* transistor (MJE170) to work in conjunction with the *npn*. (Be careful with connections! If you accidentally swap the transistors, they will both be on all the time, with a direct path for current to flow from the positive supply to the negative supply through the transistors. Something will burn out.) The *pnp* transistor will turn on whenever the op amp output is more negative than –0.7 V. Once it turns on the *pnp* provides the necessary current during the negative half cycles. The two transistors are working in a *push-pull* arrangement — the *npn* pushes current to the load during the positive half-cycles, and the *pnp* pulls from the load during the negative half-cycles.



  However, there is still a problem, because neither transistor is on when the output is between –0.7 V and +0.7 V. This is a *dead band* and results in *cross-over distortion*. Record a trace showing the distorted voltage waveform across the load resistor.

- The standard method to correct cross-over distortion is to adjust the DC operating points of the transistors so that at least one of them is always on, no matter what the input voltage is. This removes the dead band. The added DC biasing turns the output stage into a class AB amp. Setting up the biasing is a bit tricky, and we leave using this approach to a future lab.

However, the cross-over distortion can be reduced substantially using simple feedback. Move the feedback point from the op-amp output to the output of the push-pull transistors, as shown at right. Check the output waveform — there will be significantly less cross-over distortion. The feedback is trying to correct for the distortions caused by the dead bands. It is not perfect — you can probably still "glitches" as the sinusoid crosses zero — but it is definitely better than before. Observe the op-amp output — *now it is distorted!* To correct for the cross-over distortion, feedback introduces a compensating distortion that is fed to the transistors— one distortion cancels the other. In order for this to work well, the op amp should have a high slew rate in order to respond fast enough for the feedback to be effective. One of the features of the TL082 op amp is a fairly high slew rate of 13 V/μs.



Play around with the circuit until you are satisfied that you understand how it all works. Record enough oscilloscope traces to show the operation of this class B amplifier.

Reporting

Prepare and submit a report after you have finished the lab. Each lab group is required to submit a report (i.e. one report for two people). Be sure to include commentary describing the lab work and results, including measured quantities, calculated values, and oscilloscope traces.