Experiment #8—The Linear Regulator

Voltage regulators provide stable power for sensitive electronic circuits. In our final power supply experiment, we combine our experience with transistor amplifiers, op-amps and Zener diodes into a linear voltage regulator.

Terms to Learn

- *Linear*—a circuit in which the current and voltage can take on any value within a continuous range
- *Regulate*—to control a voltage or current such that it matches an established level
- *Setpoint*—the desired level at which the regulator output is to be maintained
- *Pass transistor*—the transistor in a regulator circuit through which current flows to the output circuit

The Linear Regulator

Figure 1A shows the block diagram of a *pass-type* voltage regulator. The *control element* is the decision-maker. It compares the output with its *setpoint* and varies the *control signal* to the *pass element* so that the output matches the setpoint. A simple example is squirting water from a hose with your thumb. The setpoint is where your eyes tell you the water is supposed to go. Your thumb is the pass element and your brain is the control element, constantly monitoring where your eyes say the water is actually going.

The control element in a linear regulator is a high-gain amplifier with one input connected to the setpoint and the other to the output. Any imbalance results in a strong response at the amplifier's output that causes the pass element to restore the output to the expected value. In our experiment, the control element will be an op-amp with the setpoint provided by a Zener diode. Figure 1B shows the complete circuit.

We can break this circuit down into three familiar parts—a Zener diode reference, an amplifier and an op-amp. The Zener diode that supplies the setpoint is the same one that we used in experiment #6 with an extra 0.1 µF capacitor to filter high-frequency noise. The pass transistor circuit is just an emitter-follower (EF) amplifier (Experiment #2) turned on its side! The EF's input is the control signal and its output is the load current. It is the job of the op-amp to supply enough base current (I_b) to the pass transistor so that its emitter current (I_e) can drive the load to the desired voltage, balancing the output and setpoint voltages at its inputs.

Testing the Linear Regulator

- The object is to design a fixed-voltage regulator that supplies 10 mA to a 470 Ω load at 5.1 V dc.
- Using Experiment #6's Zener (1N4733A) circuit and assuming that the load current going into the op-amp is very small, we can use the same 330 Ω resistor for R_z to supply current to D_z, which then supplies a 5.1 V dc setpoint.
- How much base current is needed for the transistor to drive the load?

$$I_e = I_b\,(\beta+1),\ \text{so}\ I_b = I_e / (\beta+1) \qquad \text{[Eq 1]}$$

The 2N4401 transistor's data sheet shows that its minimum dc current gain (β or h_{FE}) is 80 for an emitter current of 10 mA. That means I_b must be 125 µA or more to drive the transistor hard enough to allow I_e to reach 10 mA. This is well within the op-amp's capability.

- Take particular care to connect the op-amp's inverting (–) and noninverting (+) terminals correctly.
- Supply 12 V dc to the regulator's input—the Zener diode and output voltages should be almost identical and close to 5.1 V dc. The output of the op-amp should be about 0.7 V greater than the load voltage. How much power is the transistor dissipating?

$$P = I_e \times (V_{in} - V_{load})\ \text{and}\ I_e = V_{load} / 470\ \Omega$$

- Vary the input voltage up and down by 3 V. What is the effect on load voltage? How low can the input go before the output voltage drops?

Variable Regulators

In many cases a variable output voltage is needed. Figure 2 shows two types of variable regulators that use a single

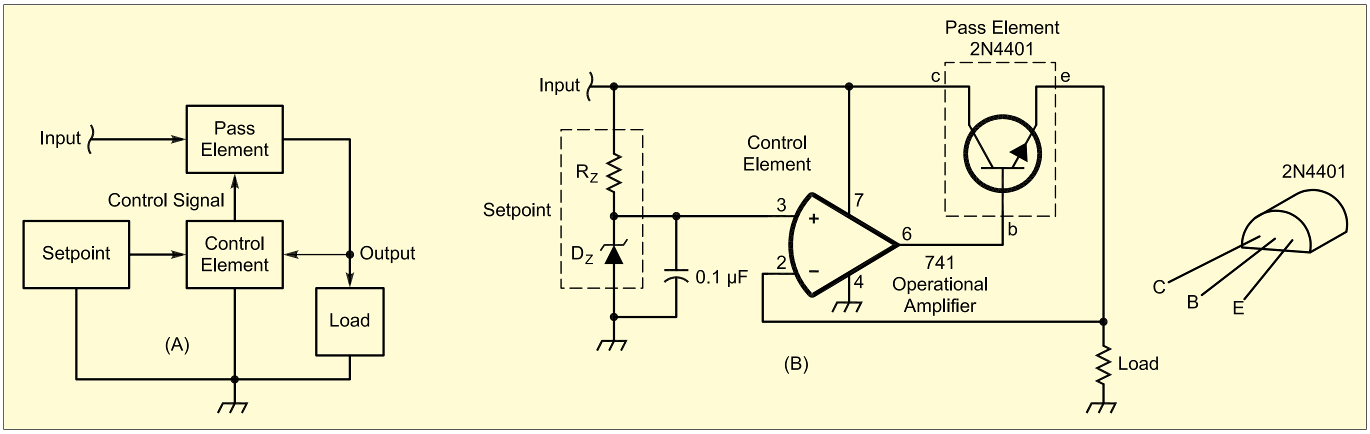

Figure 1—A: The block diagram for a pass regulator. B: The pass regulator implemented with actual components.

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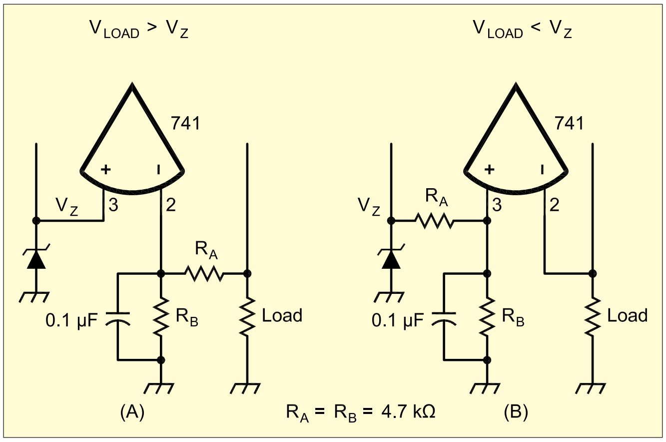

Figure 2—A: The voltage divider of R_A and R_B causes the op-amp to drive the pass transistor so that the load voltage is higher than the Zener voltage, V_Z. B: Performing the same trick for load voltages lower than V_Z.

reference Zener diode. The 0.1 µF capacitors remove high-frequency noise from the control voltages.

To regulate at load voltages greater than that of the Zener diode, a resistive voltage divider reduces the load voltage so that a fraction of the actual load voltage is supplied to the op-amp's inverting (–) terminal in Figure 2A.

$$V- = V_{load} (R_B / [R_A + R_B])$$

In order to balance its input voltages, the op-amp must drive the transistor until the load voltage is greater than the setpoint by the inverse of this fraction.

$$V_{load} = V_Z ([R_A + R_B] / R_B) \quad \text{[Eq 2]}$$

To obtain load voltages less than the Zener's voltage, use the circuit of Figure 2B. The voltage divider to reduces the Zener voltage, causing the setpoint to be reduced.

$$V_{load} = V_Z (R_B / [R_A + R_B]) \quad \text{[Eq 3]}$$

Testing a Variable Regulator

- Add two 4.7 kΩ resistors for R_A and R_B as shown in Figure 2A. The output voltage should change to nearly 10.2 V dc and the op-amp's output to around 10.9 V dc.
- Move the 4.7 kΩ resistors to divide the Zener voltage as in Figure 2B. Now the output voltage should be about 2.5 V dc and the op-amp's output about 3.2 V dc.
- Create an adjustable output regulator by replacing the two 4.7 kΩ resistors with a 10 kΩ potentiometer. Keep the 0.1 µF capacitor at the midpoint of the divider.

The Three-Terminal Regulator

There are many integrated regulators available for fixed and variable positive and negative voltages. These generally have three terminals—input, output and ground—thus creating the generic term "three-terminal regulator."

The most popular IC regulator family is the 78xx, where "xx" denotes the output voltage. A type 7805 delivers 5 V dc output, a 7812 supplies 12 V dc, and so on. The 79xx regulator series regulates negative voltages. The 78Lxx and 79Lxx are low-power regulators. There are also numerous adjustable integrated regulators, such as the LM317 shown in Figure 3. One of the earliest IC regulators was the Fairchild µA723; it's still in use. It's possible to regulate up to 10 A with an IC regulator (the TO-3 type LM396).

These packages have numerous useful features. The voltage drop from input to output can be up to 40 V dc. They can sense when they're getting too hot and shut themselves down.

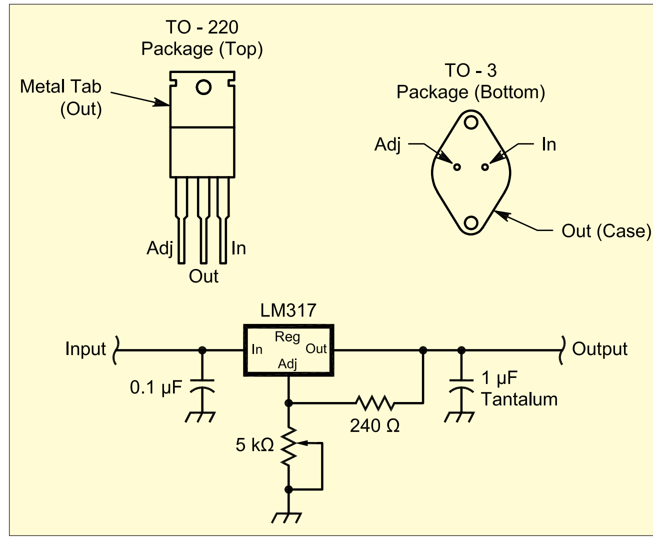

Figure 3—The LM317 adjustable three-terminal regulator is very versatile and rugged. The capacitors are required to ensure that the regulator's internal amplifiers remain stable under all conditions. The 240 Ω resistor limits the current through the 5 kΩ potentiometer. This regulator has an adjustable output from 1.2 V to a maximum that is about 3 V lower than the input voltage.

They're protected against short circuits. They have excellent regulation. You can see why they're so popular!

Two caveats, however. The regulators use high-gain amplifiers. These amplifiers can oscillate under some conditions and input and output capacitors are sometimes required, as shown in Figure 3. If overloaded, the regulators will temporarily shut themselves off until they cool, then turn back on. If the overload is persistent, this cycle can repeat as fast as tens of times per second. On a 'scope this appears as high-frequency "noise" from oscillation or a repeating "hiccup" as the chip switches between overheating and shutdown.

Try a 7805 or LM317 and learn how to use these valuable parts. Keep the current to 500 mA or less to avoid overheating the prototype board terminals.

Suggested Reading

Chapter 11 of *The ARRL Handbook* has a substantial discussion of power supply regulation. *The Art of Electronics*, by Horowitz and Hill, really shines, with page after page of Chapter 6 devoted to regulators and an excellent discussion of the 723 regulator IC.

Shopping List

- 2N4401 NPN transistor (RadioShack 276-2058)
- 470 Ω, 2 - 4.7 kΩ, 1 kΩ, 2.2 kΩ, 1/4 W resistors
- 10 kΩ potentiometer
- 2 – 0.1 µF, 50 V ceramic capacitors and a 1 µF, 35 V tantalum capacitor
- 741 op-amp (RadioShack 276-007)
- LM317 adjustable regulator (RadioShack 276-1778)

Next Month

Let's get back to basics next month with an experiment that shows how to design driver circuits for heavy loads.

This month brings a generous contribution from Steve Alpert, W1GGN. He constructed a spreadsheet that performs all the necessary calculations for the common emitter amplifier in our first experiment. It also includes a nifty lookup table for standard resistor values. It's available on the Hands-On Radio Web site: **www.arrl.org/tis/info/html/hands-on-radio/**.