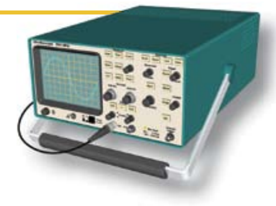
NØAX

HANDS-ON RADIO



Experiment #54 — Precision Rectifiers

Last month, we explored an RF application of a simple half-wave rectifier called a peak detector. Sometimes much more accurate rectification is required and here's how to get it.

Terms to Learn

Ideal diode — a diode with zero forward voltage drop and zero reverse current.

Linearize — change a nonlinear characteristic to a linear characteristic.

Voltage-current characteristic — the graph of voltage (X axis) versus current (Y axis) between two terminals of a device.

A Basic Op-Amp Rectifier

Passive rectifiers — those that use diodes in half or full wave configurations — are fine for rectifying large signals if the circuit is forgiving of the diode's forward voltage drop, V_F. For small signals, meaning those much smaller than V_F, passive rectifiers don't work well at all. Wouldn't it be nice if we could order an *ideal diode*? Vendors are often out of stock of ideal diodes, but we can make one by using the analog designer's favorite tool, an op-amp.

Semiconductor diodes "turn on" a little slowly before reaching a relatively constant voltage drop of 0.6 to 0.7 V (silicon) or 0.3 V (germanium). In a full wave circuit, this causes *crossover distortion* in the region the signal changes from forward to reverse current. Signals much smaller than V_F are attenuated as well, in both full and half wave circuits. By using feedback in an active circuit as shown in Figure 1, we can use the op-amp's high gain to *linearize* the nonlinear *voltage-current (V-I) characteristics* of a diode's PN junction. (A resistor's V-I characteristic is a straight line with a slope of A/V equal to its resistance in ohms.)

Figure 1 shows the basic half wave active rectifier circuit. Note the feedback connection between the cathode of D1 and the op-amp's inverting (–) input. When the input signal is positive, the op-amp's high gain causes its output to increase until the voltage at the (–) terminal (also the voltage at the diode's cathode) equals the input voltage at the noninverting (+) terminal. If you measure the op-amp's output at pin 6 you'll find it is V_F above the diode's cathode. This is true for all positive input voltages, so V_F of the whole circuit is zero!

Let's test the circuit to see the effect of feedback and gain. Connect a 1N4148 silicon diode and 10 kΩ potentiometer in series across a 12 V power supply after setting the potentiometer to full resistance. (The diode's anode should be connected to the supply's positive terminal and the cathode to the pot's adjustable terminal.) Measure voltage across the diode and current through it as the pot's resistance is reduced to 500 Ω ($I_{DIODE} = V_{SUPPLY} / R_{POT}$). You should see voltage increase slowly with current until at a few mA, V_F becomes almost constant, regardless of current. Take care not to reduce the pot's resistance much below 500 Ω to keep diode current below 25 mA.

Build the circuit of Figure 1, paying attention to op-amp pin numbers and the feedback connection. (If you connect the inverting terminal directly to the op-amp output instead of the diode's cathode, you'll just have a passive rectifier with a buffer amp driving it.) The power supply must output both +12 and –12 V so that the op-amp can operate properly with very small input signals. Connect V_{IN} to the supply's positive output and make the same plot as before. You should see that V_F (the voltage between the supply output and D1's cathode) is approximately zero for all currents through R2. (R1 provides a path for the op-amp's very small input bias current.) This circuit emulates an ideal diode and is called a *precision rectifier* because the error caused by V_F of real diodes is reduced nearly to zero. Even signals of a few mV peak-to-peak are rectified reasonably well by this circuit.

Fixing the Problems

Hold it — We're not quite finished yet! This circuit is pretty good, but it still has some shortcomings. It only has unity gain and it is just a half wave rectifier. Furthermore, when the input voltage to the circuit in Figure 1 is negative, what happens to the op-amp? It's still trying to create equal voltages at the inverting and noninverting terminals, but the diode isn't allowing any current to flow in the reverse direction, no matter how hard the op-amp tries. The op-amp output *saturates* at or near the negative supply voltage. (You can see this for yourself by connecting V_{IN} to a small negative voltage, such as from a 1.5 V battery, and measuring the op-amp output voltage.) Saturation makes the op-amp slow to recover from having all of its circuitry forced to one extreme, reducing high-frequency response of the circuit.

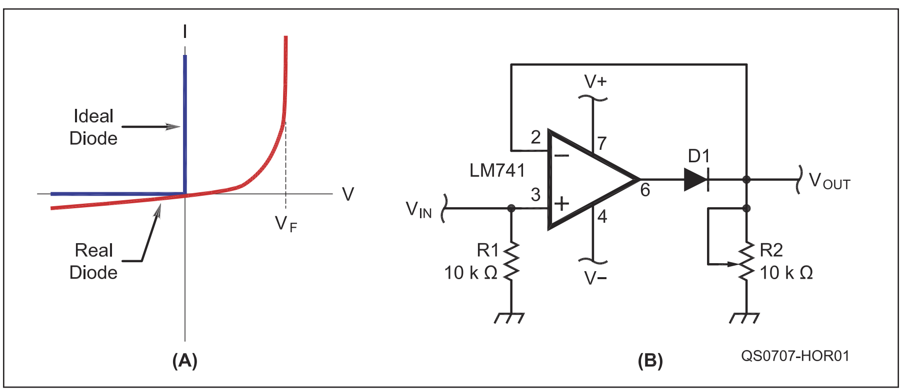


Figure 1 — The V-I characteristic curves for ideal and real diodes, showing V_F for real diodes. At B, a simple half-wave rectifier circuit with an adjustable load for measurements.

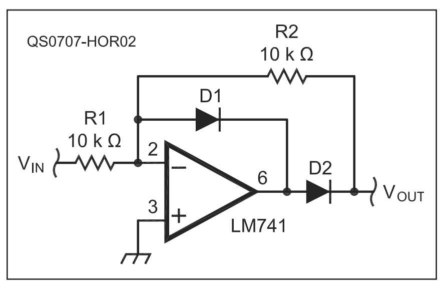


Figure 2 — A precision half-wave rectifier with adjustable gain controlled by the ratio of R1 and R2 with a diode clamp (D1) to prevent op-amp saturation.

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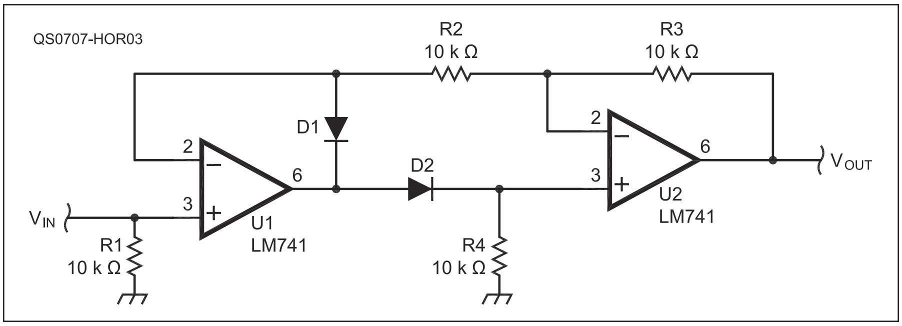

Figure 3 — Full-wave precision rectifier circuit with unity gain. D1 and D2 switch the feedback path between U2 and U1 so that the circuit alternates between inverting and noninverting gain to perform the rectification.

Variable gain is added in Figure 2, but the input signal is inverted. If D1 is removed and D2 replaced by a short circuit, the circuit becomes the standard inverting amplifier. (This circuit is described in Figure 3 of Hands-On Radio Experiment #3.[1]) For this circuit, an ac signal will be rectified such that negative inputs cause a positive output and positive inputs cause zero output. To understand the op-amp circuits in this experiment, keep in mind that the + and – inputs have a very high input impedance so that very little current flows into or out of them.

D1 solves the op-amp saturation problem. With a positive input signal, current flows from the circuit input to the inverting input of the op-amp. The op-amp balances this current with a negative output that draws current through D1 and keeps the op-amp's + and – inputs at zero volts. The op-amp output only needs to reach $–V_F$ of D1.

D2 works just as in the circuit of Figure 1. When the op-amp output goes positive (the input signal is negative), D2 conducts and supplies current to the output. The op-amp increases output voltage until the current flowing through R2 to the – input balances the current flowing to V_{IN} input through R1. The ratio of R2:R1 sets the gain of the rectifier as described in Experiment #3.

Build the circuit of Figure 2. A +12 and –12 V dc supply is required. Use 10 kΩ resistors for R1 and R2 and 1N4148 diodes for D1 and D2. If you have a signal generator and oscilloscope apply a 1 V_{PP} sine wave to the input or plot the V-I graph for both positive and negative input voltages. Confirm that the circuit half-wave rectifies the input signal and that negative input voltage results in positive output voltage. Vary the ratio of R1 and R2 to see the effect on gain.

A Full-Wave Version

Figure 3 is a full-wave rectifier circuit, easiest understood by separately analyzing negative and positive input voltages. Note that the input op-amp U1 once again has its + input connected to the circuit input so that its output voltage will be the same polarity as the input voltage. R1 and R4 provide a path to ground for input bias currents as before.

For positive input voltages, U1's output is also positive. The output is connected through D2 to the noninverting input of U2. U2's output also rises until its + and – inputs are at the same voltage. At this point, the – inputs of U1 and U2 are at the same because very little current is flowing through R2 or D1. The output of U1 continues to rise until its + and – inputs are equal. The output of U2 follows the input signal, supplying the positive half-cycle to the circuit output.

For negative input voltages, U1's output is also negative, reverse biasing D2 so it acts as an open circuit. U1's negative output pulls current through D1 and R2. U2's output rises until the current flowing in R3 exactly balances the current flowing in R2. If R2 and R3 are equal and their currents are equal, the voltage at the output of U2 will be equal and opposite polarity to the voltage at the – input of U1. U1's output raises the current through D1 and R2 until the voltage at its – input equals the input voltage. So the output of U2 is also positive for negative input signals as D1 and D2 switch the current paths.

Build the circuit of Figure 3 and confirm its positive output for both input polarities. What happens when you change the ratio of R2 and R3? Their ratio only affects the gain when the input is negative! Increase the frequency of the input signal and determine the point at which the output is 3 dB (0.707 voltage ratio) below the input signal. This is rectifier's operating bandwidth and it is determined primarily by the speed of the op-amp. A more complex full-wave rectifier circuit with adjustable gain for both input polarities can be found at **sound.westhost.com/appnotes/an001.htm**.

Shopping List

- Four 10 kΩ, ¼ W resistors.
- Two LM741 op-amps, or equivalent (a single LM747 dual op-amp will also work).
- Two 1N4148 small signal diodes.
- 10 kΩ potentiometer.

Recommended Reading

The advanced reader will find a number of interesting rectifier circuits at **www.discovercircuits.com/R/rectifier.htm**. This circuit is also covered in detail in *The Art of Electronics* and the *Op-Amp Cookbook*.[2,3]

Next Month

Now that you have your op-amps all wired up, let's have some more fun with them by creating voltage-to-current and current-to-voltage converters!

[1] **www.arrl.org/tis/info/HTML/Hands-On-Radio/**.

[2] Horowitz and Hill, *The Art of Electronics*, Chapter 4, Cambridge University Press.

[3] W. Jung, *Op-Amp Cookbook*, Chapter 5, Prentice-Hall.

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