12.9 PRECISION RECTIFIER CIRCUITS

Rectifier circuits were studied in Chapter 3, where the emphasis was on their application in power-supply design. In such applications the voltages being rectified are usually much greater than the diode voltage drop, rendering the exact value of the diode drop unimportant to the proper operation of the rectifier. Other applications exist, however, where this is not the case. For instance, the signal to be rectified can be of a very small amplitude, say 0.1 V, making it impossible to employ the conventional rectifier circuits. Also, in instrumentation applications the need arises for rectifier circuits with very precise transfer characteristics.

In this section we study circuits that combine diodes and op amps to implement a variety of rectifier circuits with precise characteristics. Precision rectifiers, which can be considered a special class of wave-shaping circuits, find application in the design of instrumentation systems.

Precision Half-wave Rectifier—The "Superdiode"

Figure 12.33(a) shows a precision half-wave-rectifier circuit consisting of a diode placed in the negative-feedback path of an op amp, with R being the rectifier load resistance. The circuit works as follows: If v_I goes positive, the output voltage v_A of the op amp will go

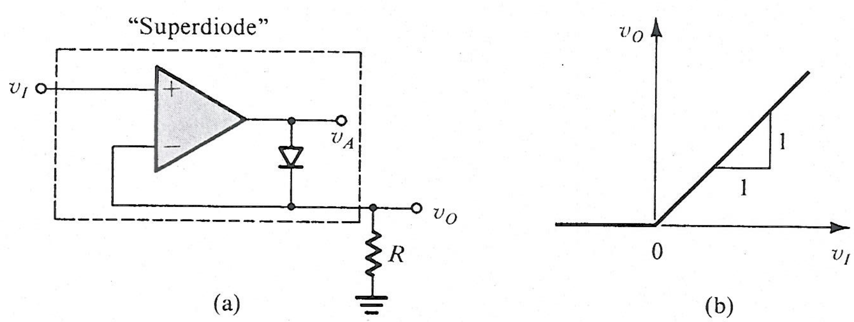

Fig. 12.33 The "superdiode" precision half-wave rectifier and its almost ideal transfer characteristic. Note that when $v_I > 0$ and the diode conducts, the op amp supplies the load current and the source is conveniently buffered, an added advantage.

positive and the diode will conduct, thus establishing a closed feedback path between the op amp's output terminal and the negative input terminal. This negative-feedback path will cause a virtual short circuit to appear between the two input terminals. Thus the voltage at the negative input terminal, which is also the output voltage v_O, will equal (to within a few millivolts) that at the positive input terminal, which is the input voltage v_I,

$$v_O = v_I \qquad v_I \geq 0$$

Note that the offset voltage ($\simeq 0.5$ V) exhibited in the simple half-wave rectifier circuit is no longer present. For the op amp circuit to start operation, v_I has to exceed only a negligibly small voltage equal to the diode drop divided by the op amp's open-loop gain.

In other words, the straight-line transfer characteristic v_O–v_I almost passes through the origin. This makes this circuit suitable for applications involving very small signals.

Consider now the case when v_I goes negative. The op amp's output voltage v_A will tend to follow and go negative. This will reverse-bias the diode, and no current will flow through resistance R, causing v_O to remain equal to 0 V. Thus for $v_I < 0$, $v_O = 0$. Since in this case the diode is off, the op amp will be operating in an open loop and its output will be at the negative saturation level.

The transfer characteristic of this circuit will be that shown in Fig. 12.33(b), which is almost identical to the ideal characteristic of a half-wave rectifier. The nonideal diode characteristics have been almost completely masked by placing the diode in the negative-feedback path of an op amp. This is another dramatic application of negative feedback. The combination of diode and op amp, shown in the dotted box in Fig. 12.33(a), is appropriately referred to as a "superdiode."

As usual, though, not all is well. The circuit of Fig. 12.33 has some disadvantages: When v_I goes negative and $v_O = 0$, the entire magnitude of v_I appears between the two input terminals of the op amp. If this magnitude is greater than few volts, the op amp may be damaged unless it is equipped with what is called "overvoltage protection" (a feature that most modern IC op amps have). Another disadvantage is that when v_I is negative, the op amp will be saturated. Although not harmful to the op amp, saturation should usually be avoided, since getting the op amp out of the saturation region and back into its linear region of operation requires some time. This time delay will obviously slow down circuit operation and limit the frequency of operation of the superdiode half-wave-rectifier circuit.

An Alternative Circuit

An alternative precision rectifier circuit that does not suffer from the disadvantages mentioned above is shown in Fig. 12.34. The circuit operates in the following manner: For positive v_I, diode D_2 conducts and closes the negative-feedback loop around the op amp. A virtual ground therefore will appear at the inverting input terminal, and the op amp's

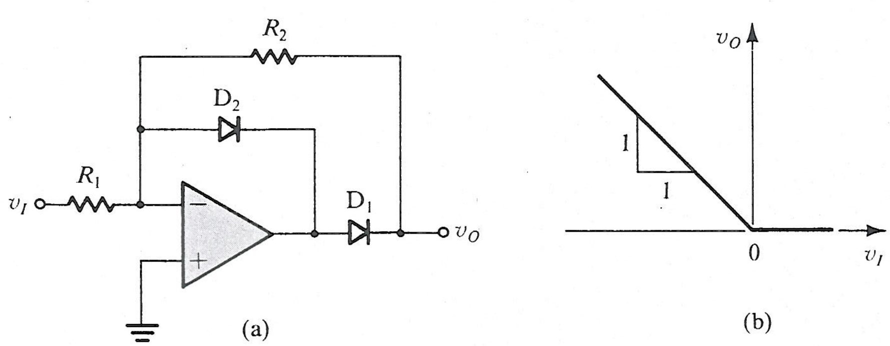

Fig. 12.34 (a) An improved version of the precision half-wave rectifier. Here diode D_2 is included to keep the feedback loop closed around the op amp during the off times of the rectifier diode D_1, thus preventing the op amp from saturating. **(b)** The transfer characteristic for $R_2 = R_1$.

output will be *clamped* at one diode drop below ground. This negative voltage will keep diode D_1 off, and no current will flow in the feedback resistance R_2. It follows that the rectifier output voltage will be zero.

As v_I goes negative, the voltage at the inverting input terminal will tend to go negative, causing the voltage at the op amp's output terminal to go positive. This will cause D_2 to be reverse-biased and hence cut off. Diode D_1, however, will conduct through R_2, thus establishing a negative-feedback path around the op amp and forcing a virtual ground to appear at the inverting input terminal. The current through the feedback resistance R_2 will be equal to the current through the input resistance R_1. Thus for $R_1 = R_2$ the output voltage v_O will be

$$v_O = -v_I \qquad v_I \le 0$$

The transfer characteristic of the circuit is shown in Fig. 12.34(b). Note that unlike for the previous circuit, here the slope of the characteristic can be set to any desired value, including unity, by selecting appropriate values for R_1 and R_2.

As mentioned before, the major advantage of this circuit is that the feedback loop around the op amp remains closed at all times. Hence the op amp remains in its linear operating region, avoiding the possibility of saturation and the associated time delay required to "get out" of saturation. Diode D_2 "catches" the output voltage as it goes negative and clamps it to one diode drop below ground; hence D_2 is called a "catching diode."

An Application: Measuring AC Voltages

As one of the many possible applications of the precision rectifier circuits discussed in this section, consider the basic ac voltmeter circuit shown in Fig. 12.35. The circuit consists of a half-wave rectifier—formed by op amp A_1, diodes D_1 and D_2, and resistors R_1 and R_2—and a first-order low-pass filter—formed by op amp A_2, resistors R_3 and R_4, and capacitor C. For an input sinusoid having a peak amplitude V_p the output v_1 of the rectifier will consist of a half sine wave having a peak amplitude of $V_p R_2/R_1$. It can be shown using Fourier series analysis that the waveform of v_1 has an average value of $(V_p/\pi)(R_2/R_1)$ in

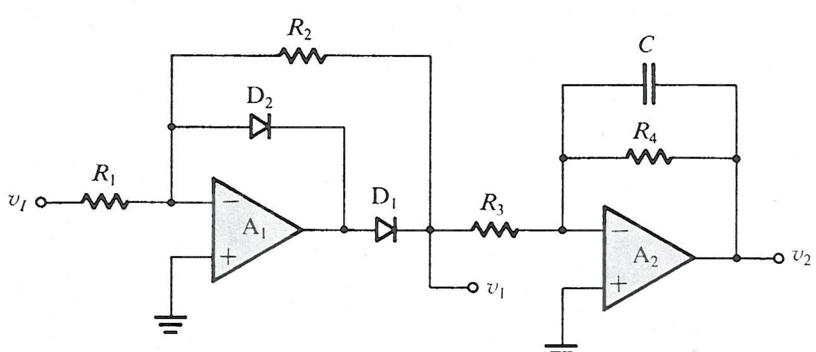

Fig. 12.35 A simple ac voltmeter consisting of a precision half-wave rectifier followed by a first-order low-pass filter.

addition to harmonics of the frequency ω of the input signal. To reduce the amplitudes of all of these harmonics to negligible levels, the corner frequency of the low-pass filter should be chosen much smaller than the lowest expected frequency ω_{min} of the input sine wave. This leads to

$$\frac{1}{CR_4} \ll \omega_{min}$$

Then the output voltage v_2 will be mostly dc, with a value

$$V_2 = -\frac{V_p}{\pi}\frac{R_2}{R_1}\frac{R_4}{R_3}$$

where R_4/R_3 is the dc gain of the low-pass filter. Note that this voltmeter essentially measures the average value of the negative parts of the input signal but can be calibrated to provide root-mean-square (rms) readings for input sinusoids.

Exercises **12.24** Consider the operational rectifier or superdiode circuit of Fig. 12.33(a), with $R = 1$ kΩ. For $v_I =$ 10 mV, 1 V, and −1 V, what are the voltages that result at the rectifier output and at the output of the op amp? Assume that the op amp is ideal and that its output saturates at ±12 V. The diode has a 0.7-V drop at 1-mA current, and the voltage drop changes by 0.1 V per decade of current change.

Ans. 10 mV, 0.51 V; 1 V, 1.7 V; 0 V, −12 V

12.25 If the diode in the circuit of Fig. 12.33(a) is reversed, find the transfer characteristic v_O as a function of v_I.

Ans. $v_O = 0$ for $v_I \geq 0$; $v_O = v_I$ for $v_I \leq 0$

12.26 Consider the circuit in Fig. 12.34(a) with $R_1 = 1$ kΩ and $R_2 = 10$ kΩ. Find v_O and the voltage at the amplifier output for $v_I = +1$ V, −10 mV, and −1 V. Assume the op amp to be ideal with saturation voltages of ±12 V. The diodes have 0.7-V voltage drops at 1 mA, and the voltage drop changes by 0.1 V per decade of current change.

Ans. 0 V, −0.7 V; 0.1 V, 0.6 V; 10 V, 10.7 V

12.27 If the diodes in the circuit of Fig. 12.34(a) are reversed, find the transfer characteristic v_O as a function of v_I.

Ans. $v_O = -(R_2/R_1)v_I$ for $v_I \geq 0$; $v_O = 0$ for $v_I \leq 0$

12.28 Find the transfer characteristic for the circuit in Fig. E12.28.

Ans. $v_O = 0$ for $v_I \geq -5$ V; $v_O = -v_I - 5$ for $v_I \leq -5$ V

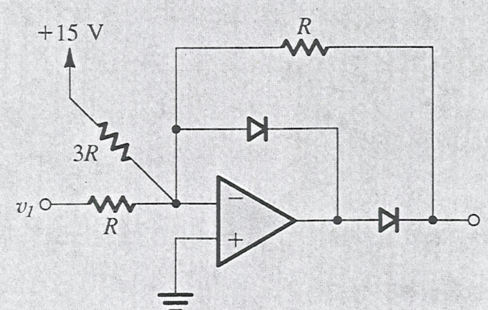

Fig. E12.28

Precision Full-Wave Rectifier

We now derive a circuit for a precision full-wave rectifier. From Chapter 3 we know that full-wave rectification is achieved by inverting the negative halves of the input-signal waveform and applying the resulting signal to another diode rectifier. The outputs of the two rectifiers are then joined to a common load. Such an arrangement is depicted in Fig. 12.36, which also shows the waveforms at various nodes. Now replacing diode D_A with a superdiode, and replacing diode D_B and the inverting amplifier with the inverting precision half-wave rectifier of Fig. 12.34 but without the catching diode, we obtain the precision full-wave rectifier circuit of Fig. 12.37(a).

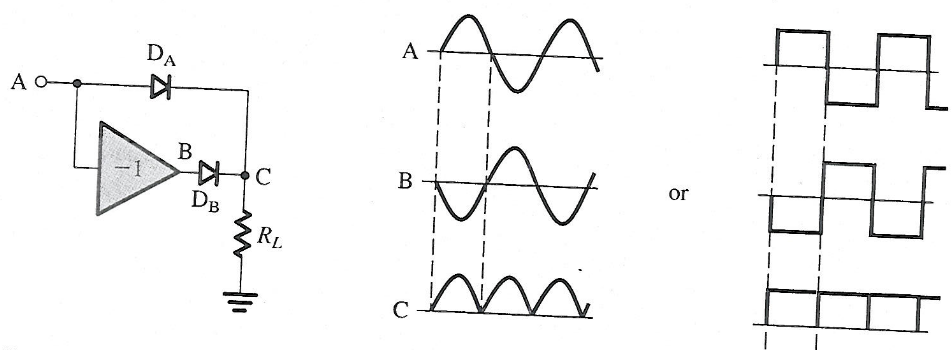

Fig. 12.36 Principle of full-wave rectification.

To see how the circuit of Fig. 12.37 operates, consider first the case where the input at A is positive. The output of A_2 will go positive, turning D_2 on, which will conduct

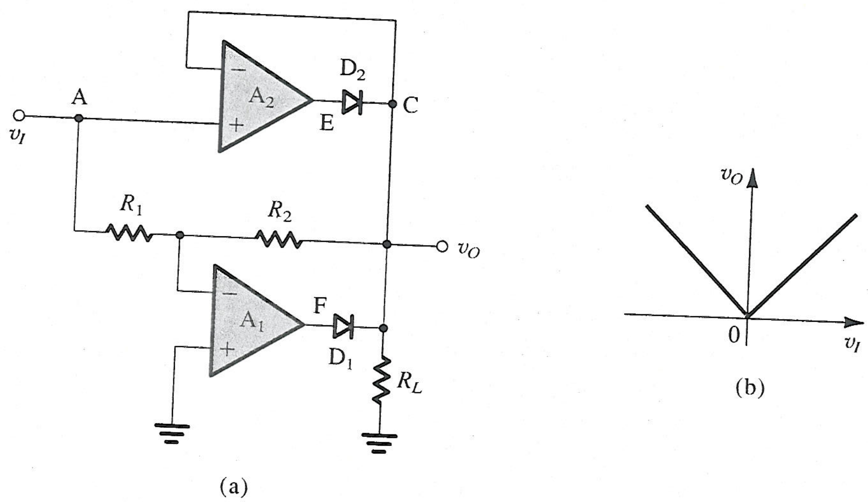

Fig. 12.37 (a) Precision full-wave rectifier based on the conceptual circuit of Fig. 12.36. **(b)** Transfer characteristic of the circuit in (a).

through R_L and thus close the feedback loop around A_2. A virtual short circuit will thus be established between the two input terminals of A_2, and the voltage at the negative input terminal, which is the output voltage of the circuit, will become equal to the input. Thus no current will flow through R_1 and R_2, and the voltage at the inverting input of A_1 will be equal to the input and hence positive. Therefore the output terminal (F) of A_1 will go negative until A_1 saturates. This causes D_1 to be turned off.

Next consider the case when A goes negative. The tendency for a negative voltage at the negative input of A_1 causes F to rise, making D_1 conduct to supply R_L and allowing the feedback loop around A_1 to be closed. Thus a virtual ground appears at the negative input of A_1, and the two equal resistances R_1 and R_2 force the voltage at C, which is the output voltage, to be equal to the negative of the input voltage at A and thus positive. The combination of positive voltage at C and negative voltage at A causes the output of A_2 to saturate in the negative direction, thus keeping D_2 off.

The overall result is perfect full-wave rectification, as represented by the transfer characteristic in Fig. 12.37(b). This precision is, of course, a result of placing the diodes in op amp feedback loops, thus masking their nonidealities. This circuit is one of many possible precision full-wave-rectifier or **absolute-value circuits.** Another related implementation of this function is examined in Exercise 12.30.

Exercises **12.29** In the full-wave rectifier circuit of Fig. 12.37(a) let $R_1 = R_2 = R_L = 10\ \text{k}\Omega$, and assume the op amps to be ideal except for output saturation at ± 12 V. When conducting a current of 1 mA each diode exhibits a voltage drop of 0.7 V, and this voltage changes by 0.1 V per decade of current change. Find v_O, v_E, and v_F corresponding to $v_I = +0.1$, $+1$, $+10$, -0.1, -1 and -10 volts.

Ans. $+0.1$ V, $+0.6$ V, -12 V; $+1$ V, $+1.6$ V, -12 V; $+10$ V, $+10.7$ V, -12 V; $+0.1$ V, -12 V, $+0.63$ V; $+1$ V, -12 V, $+1.63$ V; $+10$ V, -12 V, $+10.73$ V

D12.30 The block diagram shown in Fig. E12.30(a) gives another possible arrangement for implementing the absolute-value or full-wave-rectifier operation depicted symbolically in Fig. E12.30(b). As shown, the block diagram consists of two boxes: a half-wave rectifier, which can be implemented by the circuit in Fig. 12.34(a) after reversing both diodes, and a weighted inverting summer. Convince yourself that this block diagram does in fact realize the absolute-value operation. Then draw a complete circuit diagram, giving reasonable values for all resistors.

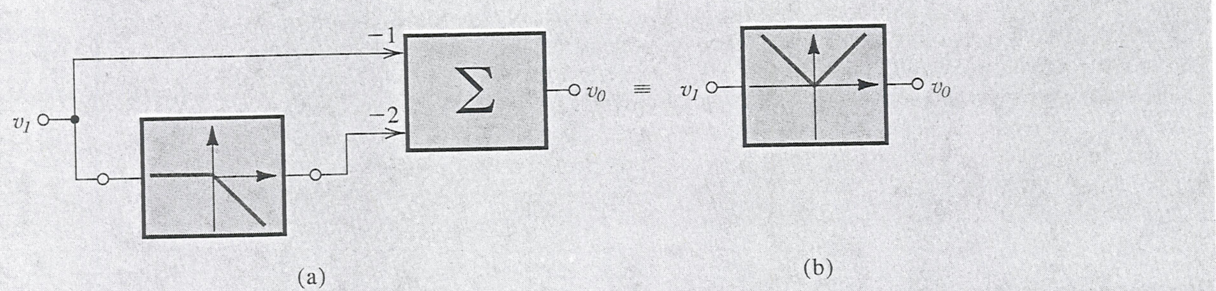

Fig. E12.30

A Precision Bridge Rectifier for Instrumentation Applications

The bridge rectifier circuit studied in Chapter 3 can be combined with an op amp to provide useful precision circuits. One such arrangement is shown in Fig. 12.38. This