18.9 Precision Rectifier Circuits

Rectifier circuits were studied in Chapter 4, 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, in instrumentation applications, 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.

Here 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. An introduction to precision rectifiers was presented in Section 4.5.5. This material, however, is repeated here for the reader’s convenience.

18.9.1 Precision Half-Wave Rectifier: The “Superdiode”

Figure 18.35(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 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 of the op amp. 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 \( v_I \),

\[
v_O = v_I \quad v_I \geq 0
\]

Note that the offset voltage (\( \approx 0.5 \) 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 \( R \), so that \( v_O \) remains 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 fashion and its output will be at the negative saturation level.

The transfer characteristic of this circuit will be that shown in Fig. 18.35(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 dashed box in Fig. 18.35(a), is appropriately referred to as a “superdiode.”

As usual, though, not all is well. The circuit of Fig. 18.35 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 a few volts, the op amp may be damaged unless it is equipped with what is called “overvoltage protection” (a feature that most modern IC
Figure 18.35 (a) The “superdiode” precision half-wave rectifier; (b) 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.

Figure 18.36 (a) An improved version of the precision half-wave rectifier: 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 $R_2 = R_1$.

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.

18.9.2 An Alternative Circuit

An alternative precision rectifier circuit that does not suffer from the disadvantages mentioned above is shown in Fig. 18.36. 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 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
18.9 Precision Rectifier Circuits

Reverse-biased and hence to be 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

\[
v_o = -v_i \quad v_i \leq 0
\]

The transfer characteristic of the circuit is shown in Fig. 18.36(b). Note that unlike the situation for the circuit shown in Fig. 18.35, 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 the improved half-wave-rectifier 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 op-amp output voltage as it goes negative and clamps it to one diode drop below ground; hence \( D_2 \) is called a “catching diode.”

### 18.9.3 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. 18.37. 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 \( v_i \) 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 \( v_i \) has an average value of \( (V_p/\pi)(R_2/R_1) \) in addition to

![Figure 18.37](image)

**Figure 18.37** A simple ac voltmeter consisting of a precision half-wave rectifier followed by a first-order low-pass filter.

### EXERCISES

18.27 Consider the operational rectifier or superdiode circuit of Fig. 18.35(a), with \( R = 1 \, k\Omega \). 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

18.28 If the diode in the circuit of Fig. 18.35(a) is reversed, what is 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 \( v_i \leq 0 \)

18.29 Consider the circuit in Fig. 18.36(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 a 0.7-V voltage drop at 1 mA, and the voltage drop changes by 0.1 V per decade of current change.

**Ans.** 0 V, −0.07 V; 0.1 V, 0.6 V; 10 V, 10.7 V

18.30 If the diodes in the circuit of Fig. 18.36(a) are reversed, what is 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 \( v_i \leq 0 \)

18.31 Find the transfer characteristic for the circuit in Fig. E18.31.

**Figure E18.31**

**Ans.** \( v_o = 0 \) for \( v_i \geq -5 \) V; \( v_o = -v_i - 5 \) for \( v_i \leq -5 \) V

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

\[
\frac{1}{CR_4} \ll \omega_{\text{min}}
\]

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 \( R_2/R_3 \) 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 rms readings for input sinusoids.
18.9.4 Precision Full-Wave Rectifier

We now derive a circuit for a precision full-wave rectifier. From Chapter 4 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. 18.38, 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. 18.36 but without the catching diode, we obtain the precision full-wave-rectifier circuit of Fig. 18.39(a).

To see how the circuit of Fig. 18.39(a) operates, consider first the case of positive input at A. The output of $A_2$ will go positive, turning $D_2$ on, which will conduct 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 what happens 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...
The block diagram shown in Fig. E18.33(a) gives another possible arrangement for implementing the absolute-value or full-wave-rectifier operation depicted symbolically in Fig. E18.33(b). The block diagram consists of two boxes: a half-wave rectifier, which can be implemented by the circuit in Fig. 18.36(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.

The overall result is perfect full-wave rectification, as represented by the transfer characteristic in Fig. 18.39(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 18.33.
18.9 Precision Rectifier Circuits

18.9.5 A Precision Bridge Rectifier for Instrumentation Applications

The bridge rectifier circuit studied in Section 4.5.3 can be combined with an op amp to provide useful precision circuits. One such arrangement is shown in Fig. 18.40. This circuit causes a current equal to $|v_A|/R$ to flow through the moving-coil meter $M$. Thus the meter provides a reading that is proportional to the average of the absolute value of the input voltage $v_A$. All the nonidealities of the meter and of the diodes are masked by placing the bridge circuit in the negative-feedback loop of the op amp. Observe that when $v_A$ is positive, current flows from the op-amp output through $D_1, M, D_3,$ and $R$. When $v_A$ is negative, current flows into the op-amp output through $R, D_2, M,$ and $D_4$. Thus the feedback loop remains closed for both polarities of $v_A$. The resulting virtual short circuit at the input terminals of the op amp causes a replica of $v_A$ to appear across $R$. The circuit of Fig. 18.40 provides a relatively accurate high-input-impedance ac voltmeter using an inexpensive moving-coil meter.

EXERCISE

D18.34 In the circuit of Fig. 18.40, find the value of $R$ that would cause the meter to provide a full-scale reading when the input voltage is a sine wave of 5 V rms. Let meter $M$ have a 1-mA, 50-Ω movement (i.e., its resistance is 50 Ω, and it provides full-scale deflection when the average current through it is 1 mA). What are the approximate maximum and minimum voltages at the op amp’s output? Assume that the diodes have constant 0.7-V drops when conducting.

Ans. 4.5 kΩ; +8.55 V; −8.55 V
18.9.6 Precision Peak Rectifiers

Including the diode of the peak rectifier studied in Section 4.5.4 inside the negative-feedback loop of an op amp, as shown in Fig. 18.41, results in a precision peak rectifier. The diode–op-amp combination will be recognized as the superdiode of Fig. 18.35(a). Operation of the circuit in Fig. 18.41 is quite straightforward. For \( v_I \) greater than the output voltage, the op amp will drive the diode on, thus closing the negative-feedback path and causing the op amp to act as a follower. The output voltage will therefore follow that of the input, with the op amp supplying the capacitor-charging current. This process continues until the input reaches its peak value. Beyond the positive peak, the op amp will see a negative voltage between its input terminals. Thus its output will go negative to the saturation level and the diode will turn off. Except for possible discharge through the load resistance, the capacitor will retain a voltage equal to the positive peak of the input. Inclusion of a load resistance is essential if the circuit is required to detect reductions in the magnitude of the positive peak.

18.9.7 A Buffered Precision Peak Detector

When the peak detector is required to hold the value of the peak for a long time, the capacitor should be buffered, as shown in the circuit of Fig. 18.42. Here op amp \( A_2 \), which should have high input impedance and low input bias current, is connected as a voltage follower. The remainder of the circuit is quite similar to the half-wave-rectifier circuit of Fig. 18.42. While diode \( D_1 \) is the essential diode for the peak-rectification operation, diode \( D_2 \) acts as a catching diode to prevent negative saturation, and the associated delays, of op amp \( A_1 \). During the holding state, follower \( A_2 \) supplies \( D_2 \) with a small current through \( R \). The output of op amp \( A_1 \) will then be clamped at one diode drop below the input voltage. Now if the input \( v_I \)
increases above the value stored on \( C \), which is equal to the output voltage \( v_o \). Op amp \( A_1 \) sees a net positive input that drives its output toward the positive saturation level, turning off diode \( D_2 \). Diode \( D_1 \) is then turned on and capacitor \( C \) is charged to the new positive peak of the input, after which time the circuit returns to the holding state. Finally, note that this circuit has a low-impedance output.

18.9.8 A Precision Clamping Circuit

By replacing the diode in the clamping circuit studied in Section 4.6.2 with a “superdiode,” the precision clamp of Fig. 18.43 is obtained. Operation of this circuit should be self-explanatory.

Section 18.9: Precision Rectifier Circuits

18.54 Two superdiode circuits connected to a common-load resistor and having the same input signal have their diodes reversed, one with cathode to the load, the other with anode to the load. For a sine-wave input of 10 V peak to peak, what is the output waveform? Note that each half-cycle of the load current is provided by a separate amplifier, and that while one amplifier supplies the load current, the other amplifier idles. This idea, called class B operation (see Chapter 12), is important in the implementation of power amplifiers.

D 18.55 The superdiode circuit of Fig. 18.35(a) can be made to have gain by connecting a resistor \( R_2 \) in place of the short circuit between the cathode of the diode and the negative-input terminal of the op amp, and a resistor \( R_1 \) between the negative-input terminal and ground. Design the circuit for a gain of 2. For a 10-V peak-to-peak input sine wave, what is the average output voltage resulting?

D 18.56 Provide a design of the inverting precision rectifier shown in Fig. 18.36(a) in which the gain is \(-2\) for negative inputs and zero otherwise, and the input resistance is 100 k\( \Omega \). What values of \( R_1 \) and \( R_2 \) do you choose?

D *18.57 Provide a design for a voltmeter circuit similar to the one in Fig. 18.37, which is intended to function at frequencies of 10 Hz and above. It should be calibrated for sine-wave input signals to provide an output of +10 V for an input of 1 V rms. The input resistance should be as high as possible. To extend the bandwidth of operation, keep the gain in the ac part of the circuit reasonably small. As well, the design should result in reduction of the size of the capacitor \( C \) required. The largest value of resistor available is 1 M\( \Omega \).

18.58 Plot the transfer characteristic of the circuit in Fig. P18.58.

18.59 Plot the transfer characteristics \( v_{o1} - v_i \) and \( v_{o2} - v_i \) of the circuit in Fig. P18.59.

18.60 Sketch the transfer characteristics of the circuit in Fig. P18.60.
D 18.61 A circuit related to that in Fig. 18.40 is to be used to provide a current proportional to $v_A (v_A \geq 0)$ to a light-emitting diode (LED). The value of the current is to be independent of the diode’s nonlinearity and variability. Indicate how this may be done easily.

*18.62 In the precision rectifier of Fig. 18.40, the resistor $R$ is replaced by a capacitor $C$. What happens? For equivalent performance with a sine-wave input of 60-Hz frequency with $R = 1 \, \text{k}\Omega$, what value of $C$ should be used? What is the response of the modified circuit at 120 Hz? At 180 Hz? If the amplitude of $v_A$ is kept fixed, what new function does this circuit perform? Now consider the effect of a waveform change on both circuits (the one with $R$ and the one with $C$). For a triangular-wave input of 60-Hz frequency that produces an average meter current of 1 mA in the circuit with $R$, what does the average meter current become when $R$ is replaced with the $C$ whose value was just calculated?

*18.63 A positive-peak rectifier utilizing a fast op amp and a junction diode in a superdiode configuration, and a 10-$\mu$F capacitor initially uncharged, is driven by a series of 10-V pulses of 10-$\mu$s duration. If the maximum output current that the op amp can supply is 10 mA, what is the voltage on the capacitor following one pulse? Two pulses? Ten pulses? How many pulses are required to reach 0.5 V? 1.0 V? 2.0 V?

D 18.64 Consider the buffered precision peak rectifier shown in Fig. 18.42 when connected to a triangular input of 1-V peak-to-peak amplitude and 1000-Hz frequency. It utilizes an op amp whose bias current (directed into $A_2$) is 10 nA and diodes whose reverse leakage current is 1 nA. What is the smallest capacitor that can be used to guarantee an output ripple less than 1%?