Precision Diode Rectifiers

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Precision half-wave rectifiers

An operational amplifier can be used to linearize a non-linear function such as the transfer function of a semiconductor diode. The classic half-wave rectifier circuit shown in Figure 1 exhibits considerable distortion and truncation when the input signal level is low.

If the diode is placed in the feedback of an operational amplifier the linearity at small signal levels is greatly improved as a result of the high amplifier gain. At high signal levels the circuit functions practically as if perfect. Signals at low frequencies down to a few millivolts peak will be accurately half-wave rectified. The only limit is the open loop gain and slew rate of the operational amplifier at the highest significant harmonic of the half-wave signal. Higher gain leads to more accurate rectification.

Figure 2 illustrates the classic precision half-wave rectifier. Series capacitor, \( C_1 \), blocks DC from the circuit and \( R_1 \) provides a path for bias current to operational amplifier, \( U_1 \). Diode, \( D_1 \), conducts when \( V_{IN} \) is positive and unity-gain amplifier, \( U_2 \), buffers the rectified signal. Diode, \( D_2 \), is reversed biased and therefore not part of the circuit when the input signal is positive. Feedback from \( U_2 \) is applied to the inverting input of \( U_1 \). The action of the output of \( U_1 \) is to go to such a voltage that the signal at the inverting input matches the signal at the non-inverting input. Thus, since \( D_1 \) is in the long feedback loop of \( U_1 \), the output of \( U_2 \) matches \( V_{IN} \) during the time that \( V_{IN} \) is positive – i.e. output waveform matches input waveform even when \( V_{IN} \) is only in the low millivolt range.

When \( V_{IN} \) is negative then the output of \( U_1 \) is negative and \( D_1 \) is reversed biased – thus the non-inverting input to \( U_2 \) is zero and \( V_O \) is zero. Diode, \( D_2 \), is now forward biased and again the output of \( U_1 \) goes to the required voltage so that its inverting input matches its non-inverting input. During this time there is a voltage drop across \( R_3 \) since \( V_O \) is zero and the inverting input to \( U_1 \) is negative.

The waveform at the output of \( U_1 \) requires a very high slew rate as the output transitions from forward bias on one diode to forward bias on the other diode – note the rapid jumps in voltage at the zero crossings. When the amplifier is not capable of slewing fast enough then the leading edge of the half-cycle is truncated. A common error in using this circuit is overlooking the
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bandwidth requirement of the amplifiers. As a rough guide the gain-bandwidth product of the amplifier should be at least 100 times the frequency of the sine wave or noticeable waveform distortion will occur particularly for low amplitude input signals. With ordinary operational amplifiers the circuits shown here operate up to a few kHz and a few tens of kHz with wider bandwidth amplifiers. Accurate higher frequency operation requires advanced methods beyond the scope of this note.

An alternate form of the precision half-wave rectifier is shown in Figure 3. \( U_1 \) is an inverting amplifier so the \( V_O \) output of \( U_2 \) is the negative portion of \( V_{IN} \). \( D_1 \) conducts when \( V_{IN} \) is negative thus making a positive voltage across \( R_2 \) which is buffered by \( U_2 \). Diode, \( D_2 \), provides a feedback path when \( V_{IN} \) is positive.

Figure 4 shows a modified version of the circuit in Figure 3 to provide smooth the half-wave rectified signal into a steady DC voltage. Circuits like this are known as “average responding” and are often used in low-cost non-true-rms responding AC voltmeters. Average responding detectors are generally calibrated to produce a voltage corresponding to the rms of a sine wave and will be inaccurate for any other waveform. The average value of the rectified signal is across \( C_2 \). For a sine wave the half-wave DC average voltage is given by Equation 1. This
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equation is only true for sine waves. Square wave, triangle waves, and other waveforms have different factors. The time constant of $R_3C_2$ should generally be several hundred milliseconds.

$$V_{DC} = \frac{V_p}{\pi} = V_{rms} \frac{\sqrt{2}}{\pi} = 0.450V_{rms}$$

(1)

Figure 4: Precision half-wave rectifier with DC smoothing filter.

Precision full-wave rectifiers, a.k.a. absolute value circuits

A useful signal processing function is the absolute value circuit. The name, full-wave rectifier, is a special case application where the input signal is AC coupled to remove any DC component. That is the only distinction between the two names – the circuits are the same. The more general absolute value circuit operates from DC up to its maximum frequency and is not thought of as a rectifier although it will obviously perform that task.

The classic absolute value circuit is shown in Figure 5. Although the circuit might look complicated the analysis is simple when broken into its parts. The circuit around $U_1$ is just like that in Figure 3 except that the diodes are reversed so the voltage waveform at point X is inverted. $U_2$ and resistors, $R_3$, $R_4$, and $R_5$ is an inverting summer with a gain of -1 to $V_{IN}$ and a gain of -2 to the voltage at point X. Note that when $V_{IN}$ is negative the voltage at point X is zero, as $D_2$ is reversed biased and $D_1$ is forward biased. In that case the output voltage of $U_2$, $V_O$, is the inverted magnitude of $V_{IN}$ – the voltage at point X is zero and contributes nothing. When $V_{IN}$ is positive the voltage at point X is the negative of $V_{IN}$. The output of $U_2$ is then the negative of $V_{IN}$ minus twice the negative of $V_{IN}$ since the gain of $U_2$ to the voltage at point X is -$R_5/R_4$ which is -2. Expressed as an equation, $V_O = -V_{IN} - (-2)V_{IN} = V_{IN}$.

For proper operation all the resistors should be matched and the 5K should be very accurately half the 10K. Otherwise there will be waveform distortions and there will be considerable error for operation at low voltages in the tens of millivolts and less.
An absolute value circuit based on a dual half-wave circuit is shown in Figure 6. Analysis of the circuit is simple although a common error is omitting the effect of $R_3$. For this circuit to work properly it is important that $R_2$ and $R_3$ be matched in resistance and that $R_4$ and $R_5$ be matched as well. Ideally all four resistors match. $R_1$ just sets a scale factor and can be higher or lower than the other resistors as shown in a subsequent example. The analysis will be performed with all five resistors the identical value as shown in the figure. Operation is as follows.

When $V_{IN}$ is positive the output of $U_1$ goes negative so that the voltage at the anode of $D_2$ is $-V_{IN}$ and the voltage at the cathode of $D_1$ is zero. Thus, $U_2$ acts as an inverting amplifier and $V_O = V_{IN}$.

When $V_{IN}$ is negative the output of $U_1$ goes positive so that the voltage at the cathode of $D_1$ goes positive – an error is to assume it goes to $-V_{IN}$ – keep in mind the path through $R_3$. Let us call that voltage $V_X$. We note that the voltage at the inverting input of $U_2$ must also be $V_X$. We then note that the total feedback current to the inverting input of $U_1$ is $I_f = V_X/R_2 + V_X/(R_3 + R_4) = (3/2)(V_X/10K)$. Since this current is identical to $V_{IN}/10K$ then $V_X = -(2/3)V_{IN}$. The non-inverting gain of $U_2$ is 1.5 (remember that $R_3$ is in the circuit) so $V_O = -V_{IN}$, a positive voltage.
One undesirable trait of the circuits in Figures 5 and 6 is that considerable resistor matching is required for proper operation. Mismatching of the resistors results in a variety of distortions as shown in Figure 7. In the first case the gain is different for the two half-cycles. In the second and third cases the crossover points do not lineup in addition of gain mismatch.

The circuit shown in Figure 8 is believed to be the simplest possible absolute value circuit and has the feature that only two resistors, $R_1$ and $R_2$, need to be matched. $R_3$ is nominally the same resistance but does not need to match.

When $V_{IN}$ is positive $D_2$ is forward biased ($D_1$ is reversed biased) and $U_2$ acts as a unity gain buffer to $V_O$. Feedback through $R_1$ and $R_2$ to $U_1$ causes $V_O$ to match $V_{IN}$. When $V_{IN}$ is negative then $D_1$ is forward biased ($D_2$ is reversed biased) and the output of $U_1$ goes to the required voltage so that its inverting input matches $V_{IN}$. $U_2$ is now an inverting amplifier so that $V_O$ is $-V_{IN}$ – i.e. always positive.

One negative aspect of the circuit is that $U_2$ is in the feedback of $U_1$ for $V_{IN}$ positive. The small time delay or phase lag through that path can cause a loop oscillation. Capacitor, $C_1$, compensates for the phase lag introduced when $U_2$ is in the feedback of $U_1$. The required capacitance is inversely proportional to the bandwidth of the amplifiers and will typically be in the range of several tens to perhaps over a hundred picofarads. It is best determined by experimentation with the actual physical circuit. If the capacitance is too small some oscillation may be observed on portions of the $V_O$ waveform when $V_{IN}$ is positive. If the capacitance is too
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large, there will be errors at high frequencies. The correct amount of capacitance is as small as possible consistent with no oscillation on the $V_O$ waveform.

Figure 8: Simplest possible absolute value circuit

Figure 9 shows a precision full-wave rectifier with DC smoothing. As shown, $V_O$ is a DC voltage equal to the rms voltage of $V_{IN}$ provided that $V_{IN}$ is a sine wave. That relation will not hold true for other waveforms. The smoothing time constant set by the 330K and 1 uF capacitors is one-third of a second which gives a full settling time of about 2 seconds. $C_2$ and $C_3$ should be smaller to reduce that time. $(R_4/R_2)$ and correspondingly $(R_5/R_3)$ should be large as shown to minimize the effect of stored charge on the smoothing capacitors from affecting operation of $U_1$. $U_1$ should have wide bandwidth. $U_2$ and $U_3$ should be precision DC amplifiers and have very low input bias currents – preferably less than 1 nA.

The voltage across $R_2$ is a positive half-cycle and the voltage across $R_3$ is a negative half-cycle. Those half-cycles are DC averaged by filters, $R_4C_2$ and $R_5C_3$. The difference amplifier provides a gain of two. With $V_{IN}$ a sine wave of rms voltage, $V_{RMS}$, the DC output voltage, $V_O$ is found as follows. The two factors of 2 account for the difference amplifier applying a gain of two on the difference between the positive DC average and the negative DC average.

$$V_O = V_{RMS} \left( \frac{2.0}{3.6} \right) \left( \frac{\sqrt{2}}{\pi} \right) (2)(2) = 1.0004V_{RMS}$$

(2)
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Figure 9: Full-wave rectifier with DC smoothing filter

See the following web links for more information.

