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.

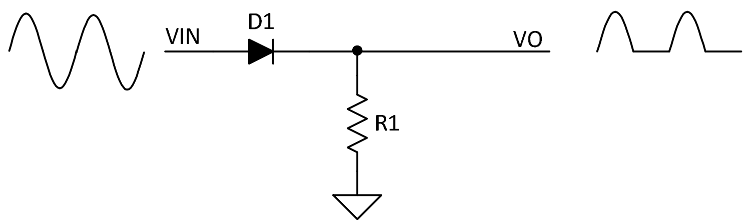

Figure 1: Simple half-wave rectifier with large signal input to minimize output distortion

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 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.

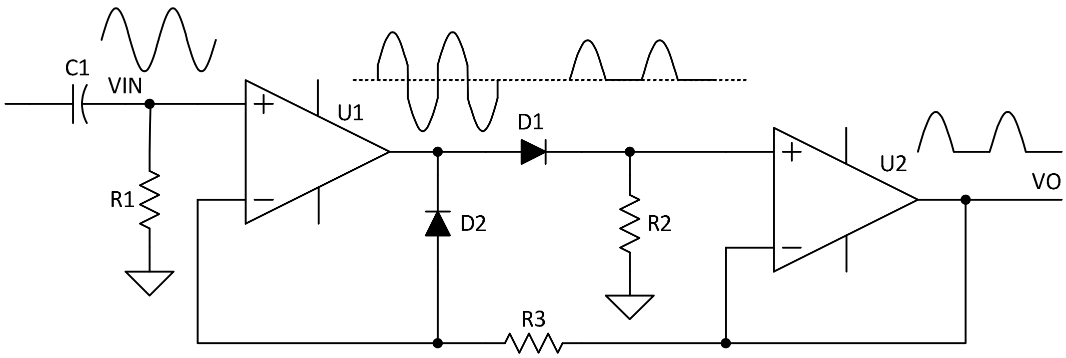

Figure 2: Precision half-wave rectifier

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.

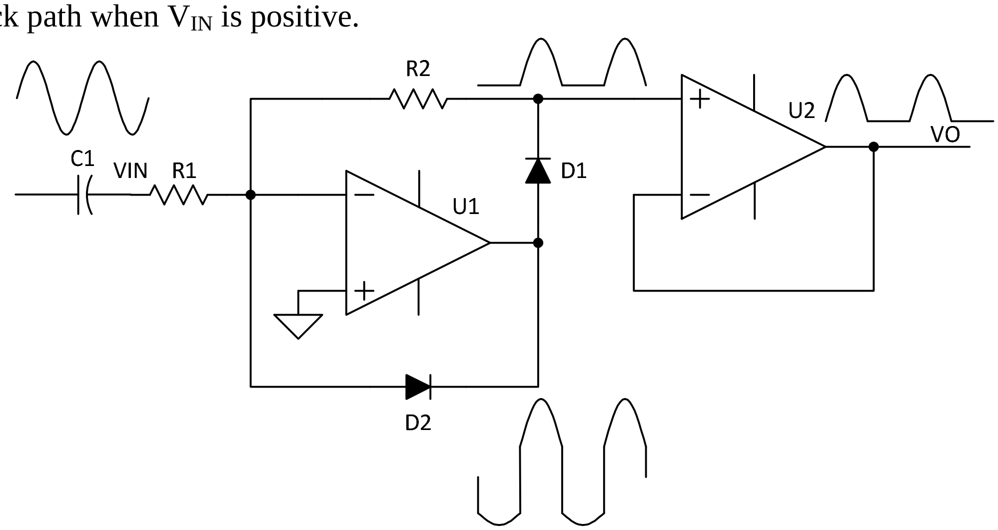

Figure 3: Alternate precision half-wave rectifier

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 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.

$$V_{DC} = \frac{V_P}{\pi} = V_{rms}\frac{\sqrt{2}}{\pi} = 0.450V_{rms} \tag{1}$$

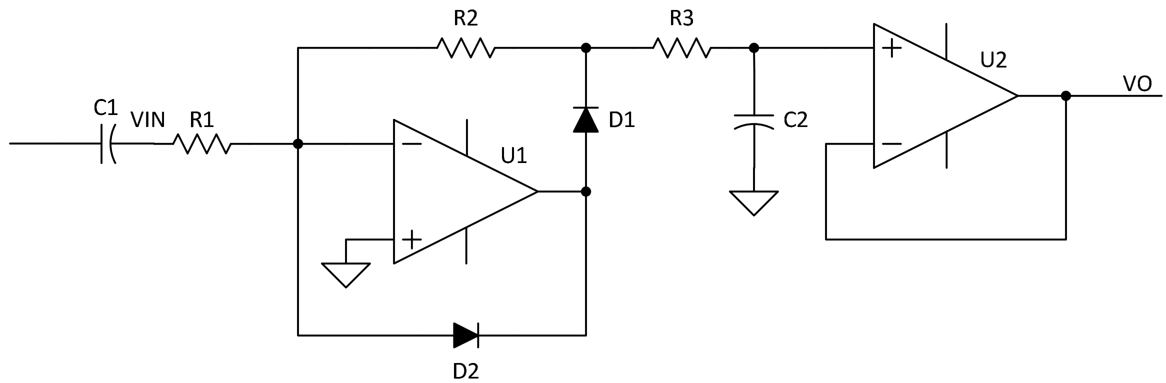

Figure 4: Precision half-wave rectifier with DC smoothing filter.

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.

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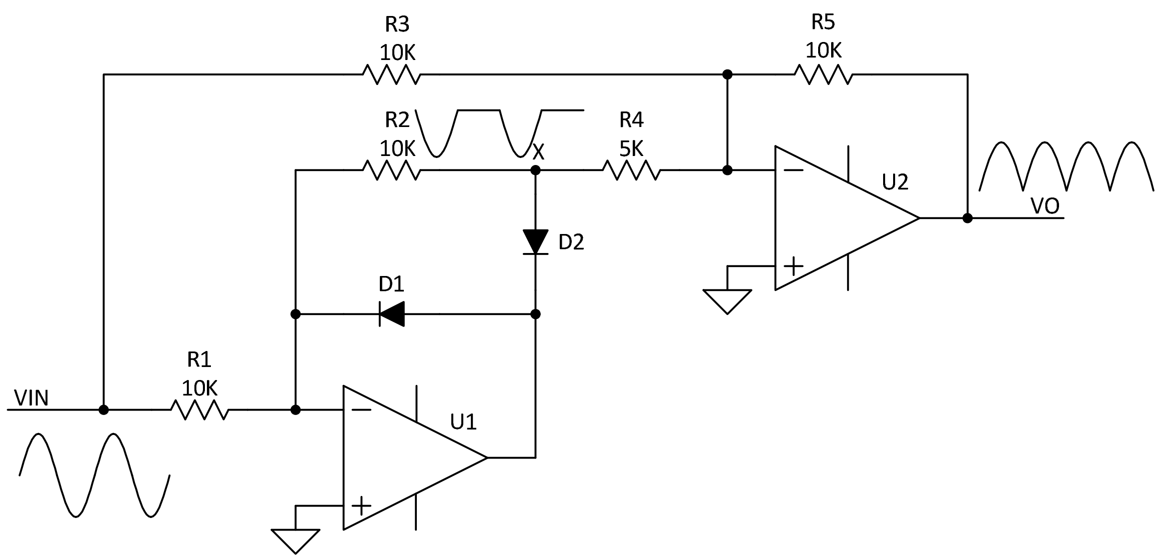

Figure 5: Classic absolute value circuit

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.

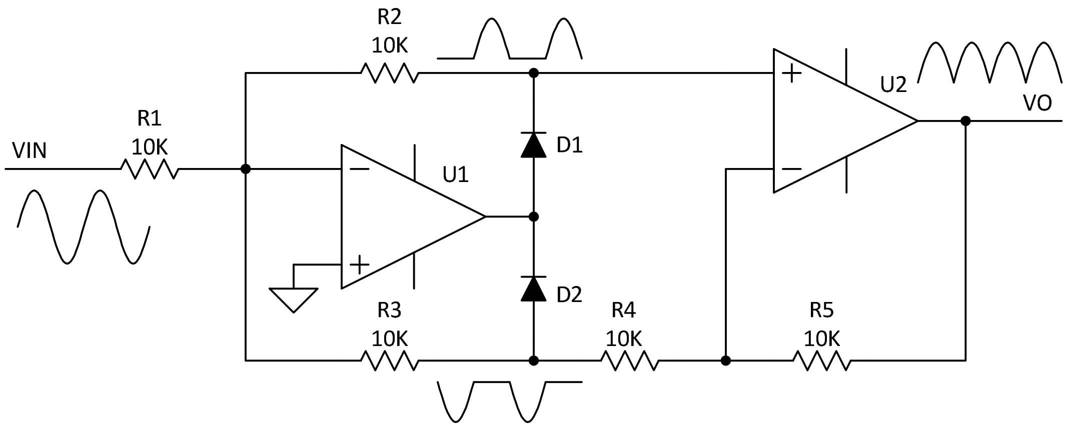

Figure 6: Alternate absolute value circuit

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.

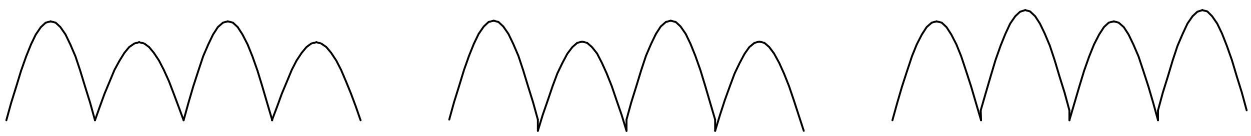

Figure 7: Examples of distortion caused by resistors not being matched

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 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.

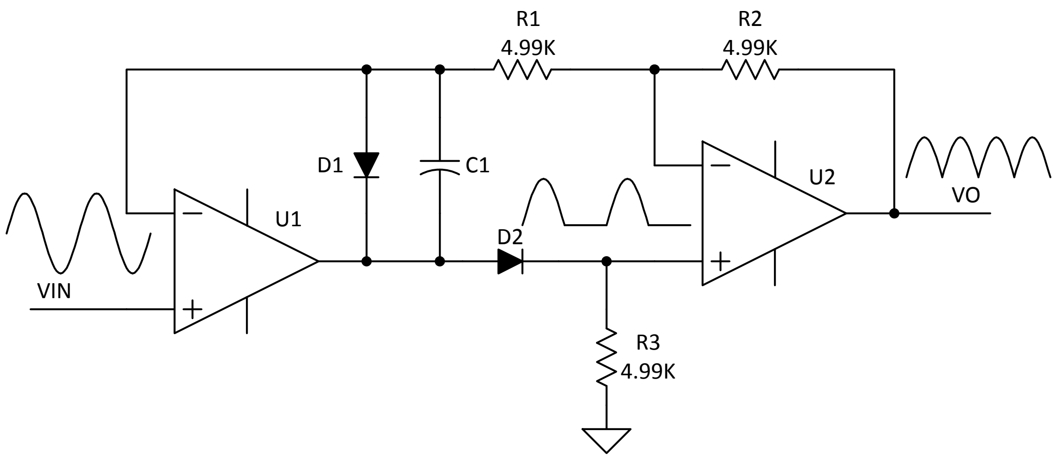

Figure 8: Simplest possible absolute value circuit

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 a two. With V_{IN} a sine wave of rms voltage, Vrms, 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.

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

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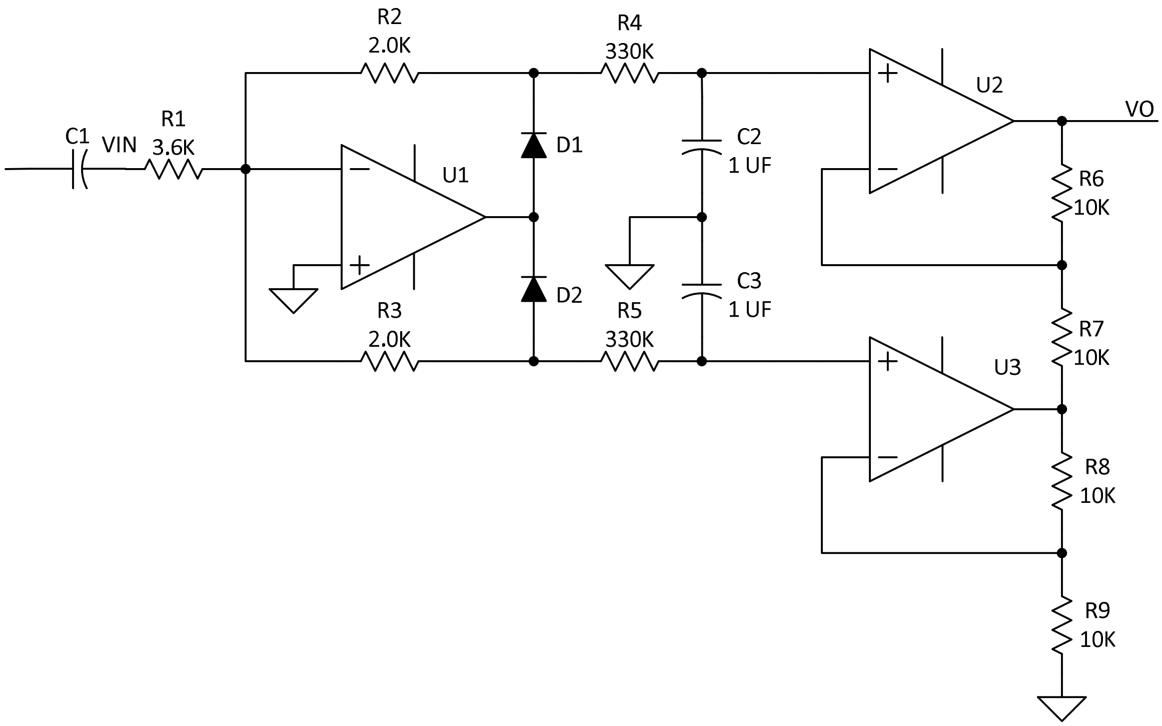

Figure 9: Full-wave rectifier with DC smoothing filter

See the following web links for more information.

http://www.ti.com/lit/an/sboa068/sboa068.pdf About the simplest possible absolute value circuit.

http://www.edn.com/file/18953-70501di.pdf An interesting absolute value circuit.

http://www.analog.com/library/analogDialogue/archives/44-04/absolute.html An interesting method of achieving absolute value using single supply op-amps.