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7-1 LINEAR HALF-WAVE RECTIFIERS

7-1.1 Introduction

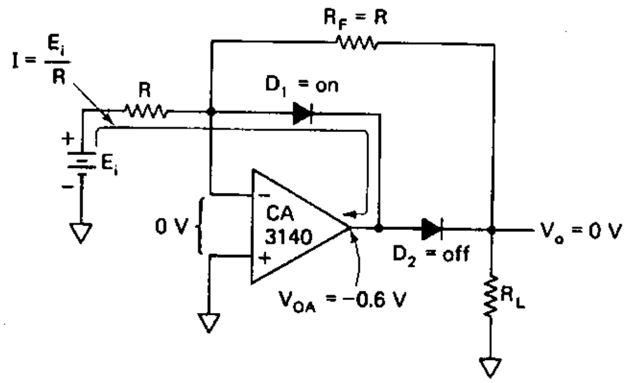
Linear half-wave rectifier circuits transmit only one-half cycle of a signal and eliminate the other by *bounding* the output to zero volts. The input half-cycle that is transmitted can be either inverted or noninverted. It can also experience gain, attenuation, or remain unchanged in magnitude, depending on the choice of resistors and placement of diodes in the op amp circuit.

7-1.2 Inverting, Linear Half-Wave Rectifier, Positive Output

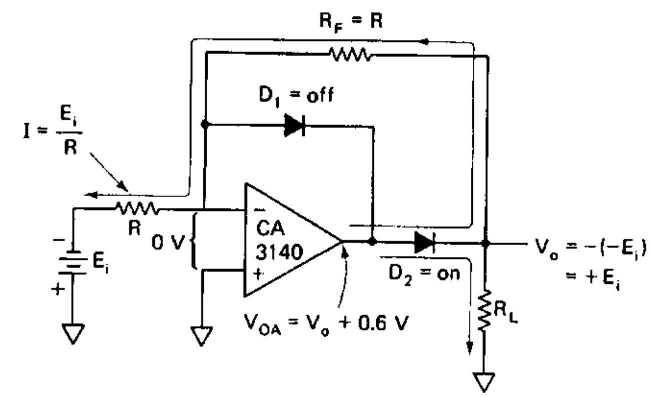
The inverting amplifier is converted into an ideal (linear precision) half-wave rectifier by adding two diodes as shown in Fig. 7-2. When E_i is positive in Fig. 7-2(a), diode D_1 conducts causing the op amp's output voltage, V_{OA}, to go negative by one diode drop ($\cong$0.6 V). This forces diode D_2 to be reverse biased. The circuit's output voltage V_o equals zero because input current I flows through D_1. For all practical purposes, no current flows through R_F and therefore $V_o = 0$.

Note the load is modeled by a resistor R_L and must always be resistive. If the load is a capacitor, inductor, voltage, or current source, then V_o will *not* equal zero.

In Fig. 7-2(b), negative input E_i forces the op amp output V_{OA} to go positive. This causes D_2 to conduct. The circuit then acts like an inverter since $R_F = R_i$ and $V_o = -(-E_i) = +E_i$. Since the $(-)$ input is at ground potential, diode D_1 is reverse biased. Input current is set by E_i/R_i and gain by $-R_F/R_i$. Remember that this gain equation applies only for negative inputs, and V_o can only be positive or zero.



(a) Output V_o is bound at 0 V for all positive input voltages



(b) Output V_o is positive and equal to the magnitude of E_i for all negative inputs

Figure 7-2 Two diodes convert an inverting amplifier into a positive-output, inverting, linear (ideal) half-wave rectifier. Output V_o is positive and equal to the magnitude of E_i for negative inputs, and V_o equals 0 V for all positive inputs. Diodes are IN914 or IN4154.

Circuit operation is summarized by the waveshapes in Fig. 7-3. V_o can only go positive in a linear response to negative inputs. The most important property of this linear half-wave rectifier will now be examined. An ordinary silicon diode or even a hot-carrier diode requires a few tenths of volts to become forward biased. Any signal voltage below this threshold voltage cannot be rectified. However, by connecting the diode in the feedback loop of an op amp, the threshold voltage of the diode is essentially eliminated. For example, in Figure 7-2(b) let E_i be a low voltage of -0.1 V. E_i and R_i convert this low voltage to a current that is conducted through D_2. V_{OA} goes to whatever voltage is required to supply the necessary diode drop plus the voltage drop across R_f. Thus millivolts of input voltage can be rectified since the diode's forward bias is supplied automatically by the negative feedback action of the op amp.

Finally, observe the waveshape of op amp output V_{OA} in Fig. 7-3. When E_i crosses 0 V (going negative), V_{OA} jumps quickly from -0.6 V to $+0.6$ V as it switches

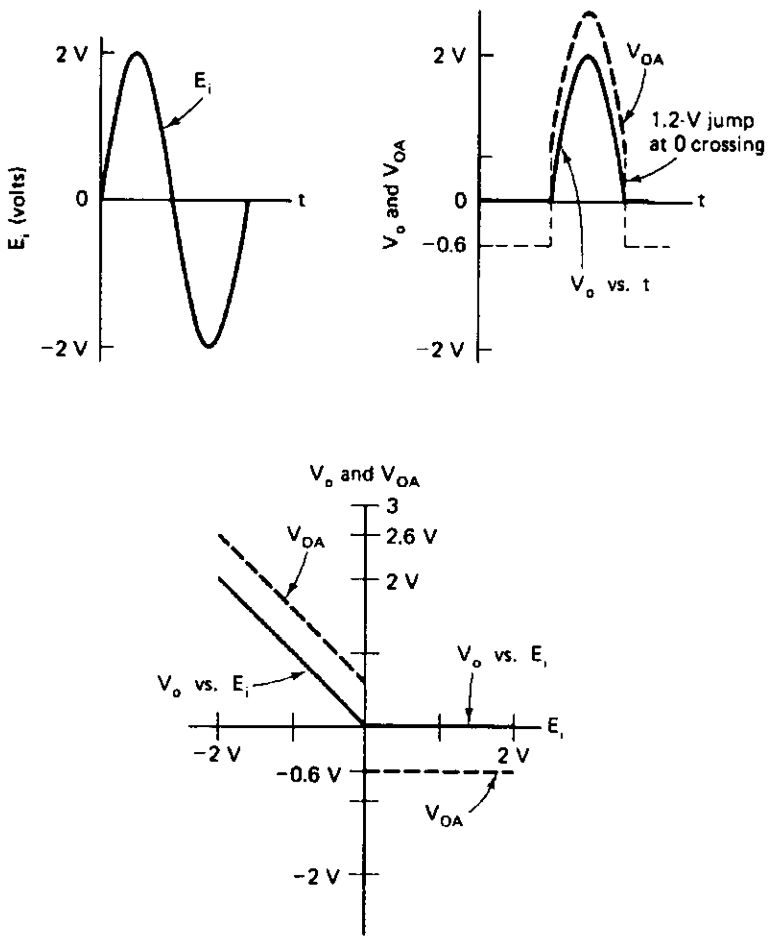
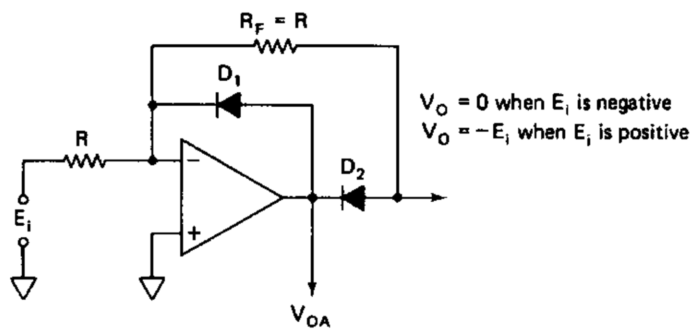


Figure 7-3 Input, output, and transfer characteristics of a positive-output, ideal, inverting half-wave rectifier.

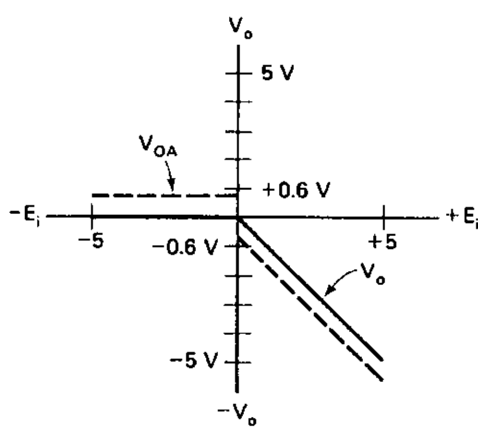
from supplying the drop for D_2 to supplying the drop for D_1. This jump can be monitored by a differentiator to indicate the zero crossing. During the jump time the op amp operates open loop.

7-1.3 Inverting Linear Half-Wave Rectifier, Negative Output

The diodes in Fig. 7-2 can be reversed as shown in Fig. 7-4. Now only positive input signals are transmitted and inverted. The output voltage V_o equals 0 V for all negative inputs. Circuit operation is summarized by the plot of V_o and V_{OA} versus E_i in Fig. 7-4(b).



(a) Inverting linear half-wave rectifier: negative output



(b) Transfer characteristic V_o vs. E_i

Figure 7-4 Reversing the diodes in Fig. 7-2 gives an inverting linear half-wave rectifier. This circuit transmits and inverts only positive input signals.

7-1.4 Signal Polarity Separator

The circuit of Fig. 7-5 is an expansion of the circuits in Figs. 7-2 and 7-4. When E_i is positive in Fig. 7-5(a), diode D_1 conducts and an output is obtained only on output V_{o1}. V_{o2} is bound at 0 V. When E_i is negative, D_2 conducts, $V_{o2} = -(-E_i) = +E_i$, and V_{o1} is bound at 0 V. This circuit's operation is summarized by the waveshapes in Fig. 7-6.

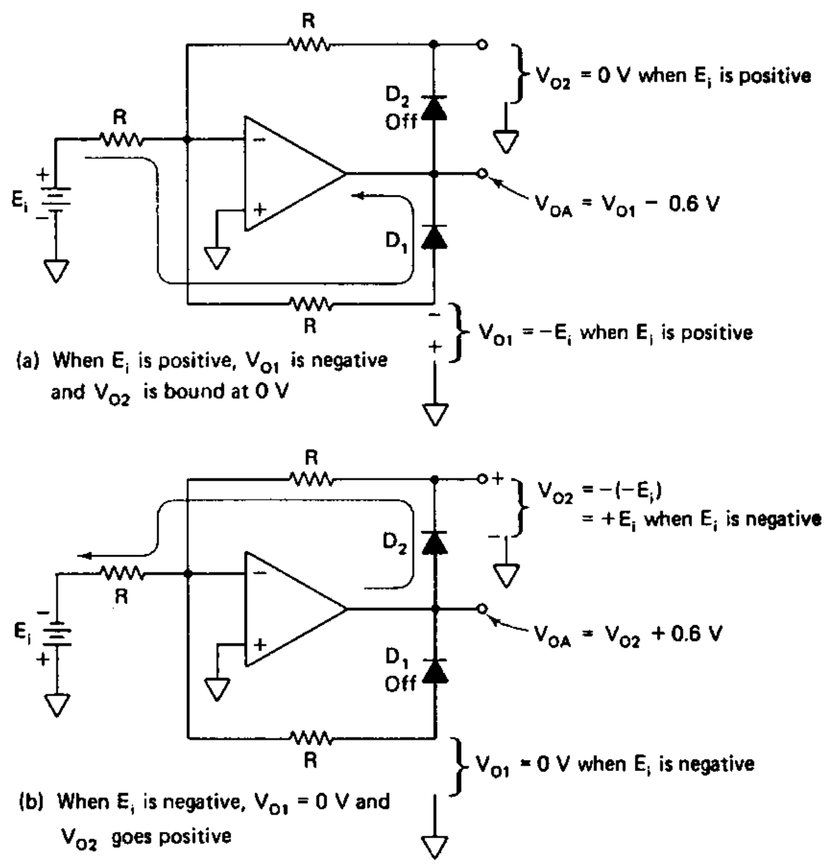


Figure 7-5 This circuit inverts and separates the polarities of input signal E_i. A positive output at V_{o2} indicates that E_i is negative and a negative output at V_{o1} indicates that E_i is positive. These outputs should be buffered.

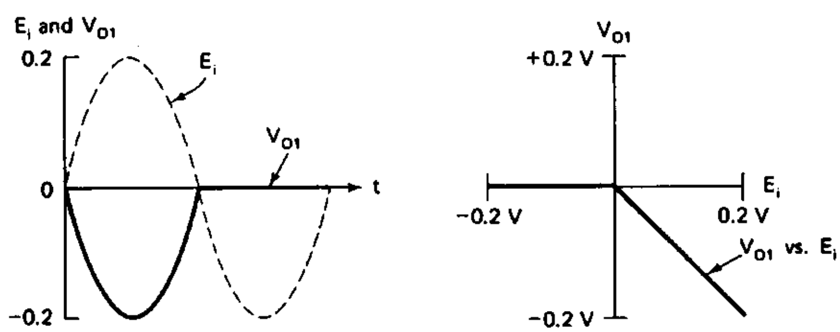


Figure 7-6 Input and output voltages for the polarity separator of Fig. 7-5.

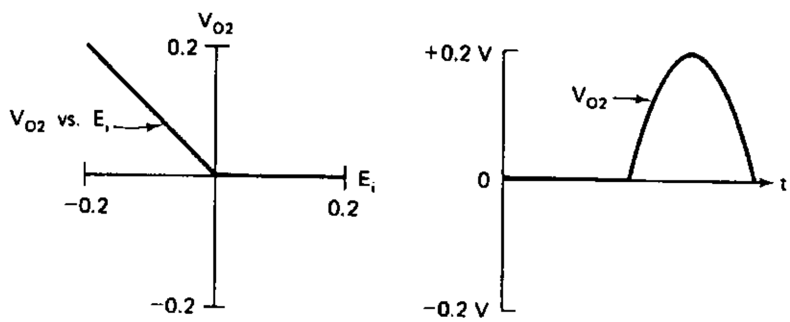


Figure 7-6 *(cont.)*

7-2 PRECISION RECTIFIERS: THE ABSOLUTE-VALUE CIRCUIT

7-2.1 Introduction

The precision full-wave rectifier transmits one polarity of the input signal and inverts the other. Thus both half-cycles of an alternating voltage are transmitted but are converted to a single polarity of the circuit's output. The precision full-wave rectifier can rectify input voltages with millivolt amplitudes.

This type of circuit is useful to prepare signals for multiplication, averaging, or demodulation. The characteristics of an ideal precision rectifier are shown in Fig. 7-7.

The precision rectifier is also called an *absolute-value* circuit. The absolute value of a number (or voltage) is equal to its magnitude regardless of sign. For example, the absolute values of $|+2|$ and $|-2|$ are equal $+2$. The symbol $|*|$ means "absolute value of." Figure 7-7 shows that the output equals the absolute value of the input. In a precision rectifier circuit the output is either negative or positive, depending on how the diodes are installed.

7-2.2 Types of Precision Full-Wave Rectifiers

Three types of precision rectifiers will be presented. The first is inexpensive because it uses two op amps, two diodes, and five *equal* resistors. Unfortunately, it does not have high input resistance, so a second type is given that does have high input resistance but requires resistors that are precisely proportioned but *not* all equal. Neither type has a summing node at virtual ground potential, so a third type will be presented in Section 7-4.2 to allow averaging.

Full-wave precision rectifier with equal resistors. The first type of precision full-wave rectifier or absolute-value circuit is shown in Fig. 7-8. This circuit uses equal resistors and has an input resistance equal to R. Figure 7-8(a) shows current directions and voltage polarities for positive input signals. Diode D_P conducts so that both op amps A and B act as inverters, and $V_o = +E_i$.

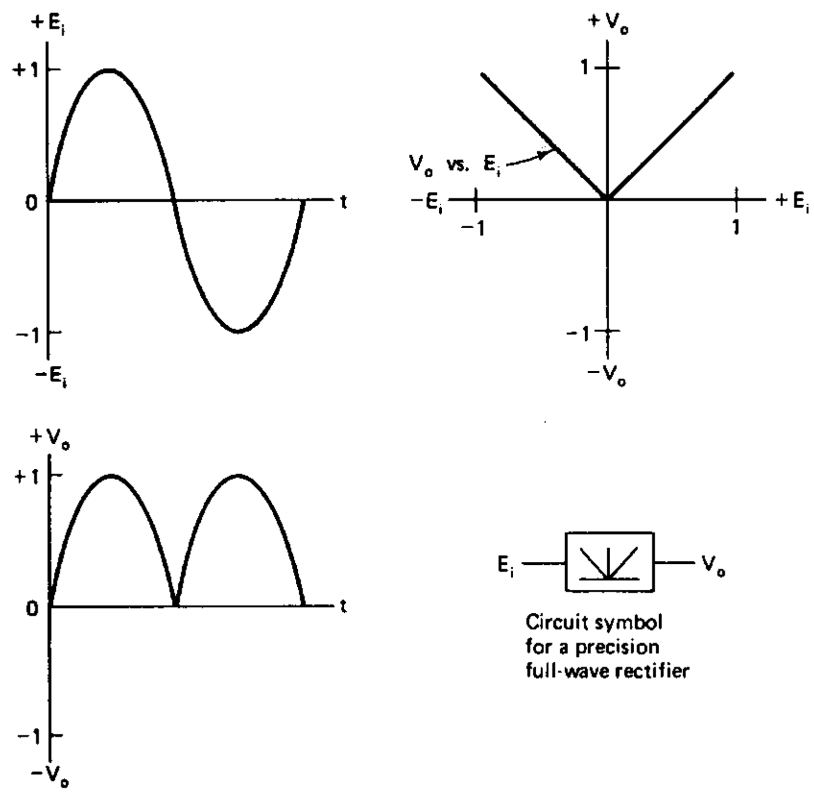


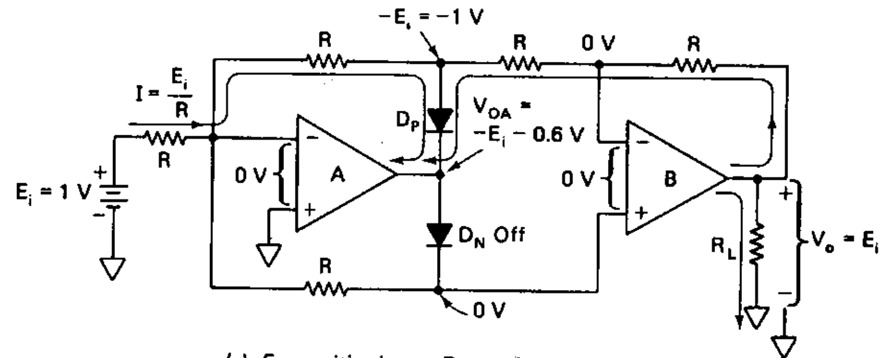
Figure 7-7 The precision full-wave rectifier fully rectifies input voltages, including those with values less than a diode threshold voltage.

Figure 7-8(b) shows that for negative input voltages, diode D_N conducts. Input current I divides as shown, so that op amp B acts as an inverter. Thus output voltage V_o is positive for either polarity of input E_i and V_o is equal to the absolute value of E_i.

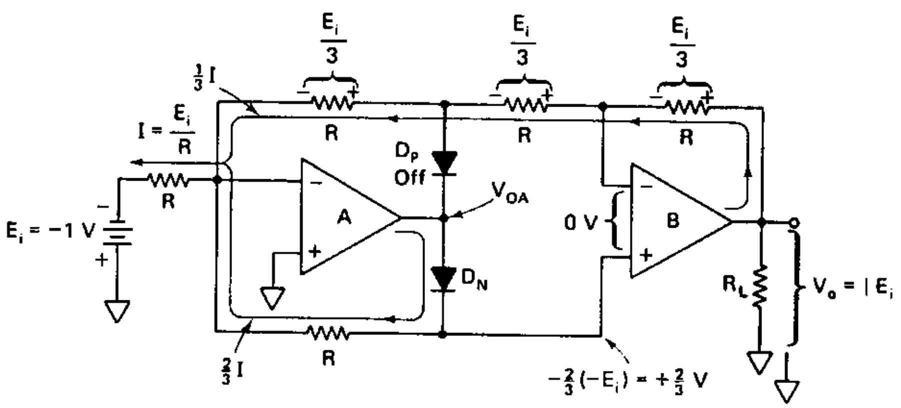
Waveshapes in Fig. 7-8(c) show that V_o is always of positive polarity and equal to the absolute value of the input voltage. To obtain negative outputs for either polarity of E_i, simply reverse the diodes.

High-impedance precision full-wave rectifier. The second type of precision rectifier is shown in Fig. 7-9. The input signal is connected to the noninverting op amp inputs to obtain high input impedance. Figure 7-9(a) shows what happens for positive inputs. E_i and R_i set the current through diode D_P. The (−) inputs of both op amps are at a potential equal to E_i so that no current flows through R_2, R_3, and R_4. Therefore, $V_o = E_i$ for all positive input voltages.

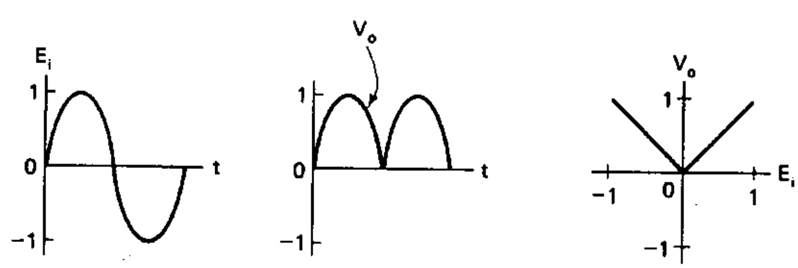
When E_i goes negative in Fig. 7-9(b), E_i and R_1 set the current through both R_1 and R_2 to turn on diode D_N. Since $R_1 = R_2 = R$, the anode of D_N goes to $2E_i$ or



(a) For positive inputs D_P conducts; op amps A and B act as inverting amplifiers

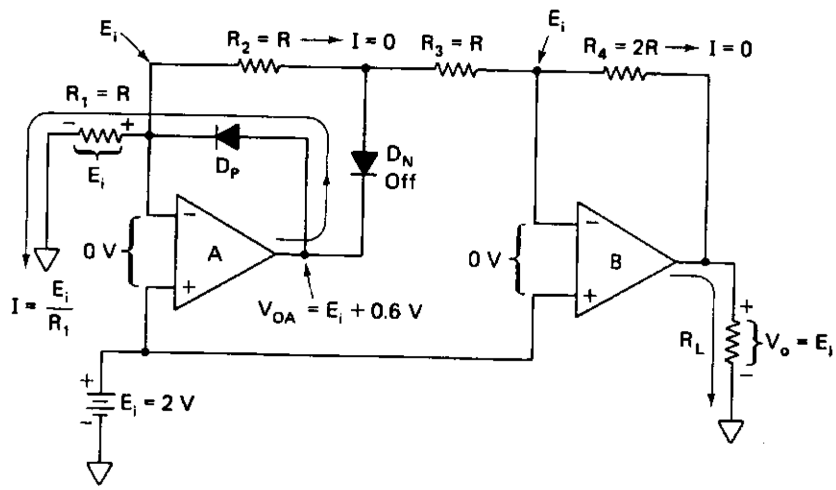


(b) For negative inputs, D_N conducts

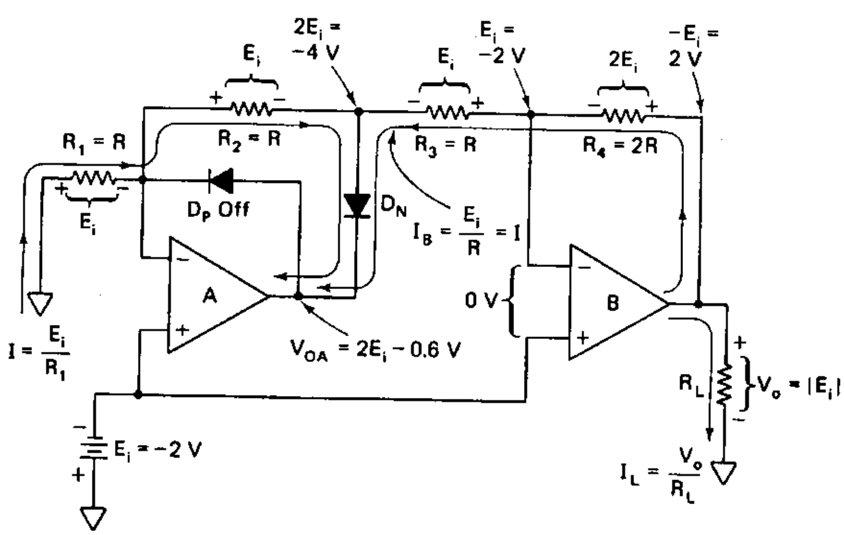


(c) Waveshapes

Figure 7-8 Absolute-value circuit or precision full-wave rectifier, $V_o = |E_i|$.



(a) Voltage levels for positive inputs: $V_o = +E_i$ for all positive E_i



(b) Voltage levels for negative inputs: $V_o = -(-E_i) = |E_i|$

Figure 7-9 Precision full-wave rectifier with high input impedance. $R = 10\ k\Omega$, $2R = 20\ k\Omega$.

$2(-E_i) = -4$ V. The (−) input of op amp B is at $-E_i$. The voltage drop across R_3 is $2E_i - E_i$ or $(-4\text{ V}) - (-2) = -2$ V. This voltage drop and R_3 establishes a current I_3 through both R_3 and R_4 equal to the input current I. Consequently, V_o is positive when E_i is negative. Thus V_o is always positive despite the polarity of E_i, so $V_o = |E_i|$.

Waveshapes for this circuit are the same as in Fig. 7-8(c). Note that the maximum value of E_i is limited by the negative saturation voltage of the op amps.

7-3 PEAK DETECTORS

In addition to precisely rectifying a signal, diodes and op amps can be interconnected to build a peak detector circuit. This circuit follows the voltage peaks of a signal and stores the highest value (almost indefinitely) on a capacitor. If a higher peak signal value comes along, this new value is stored. The highest peak voltage is stored until the capacitor is discharged by a mechanical or electronic switch. This peak detector circuit is also called a *follow-and-hold* or *peak follower*. We shall also see that reversing two diodes changes this circuit from a peak to a *valley follower*.

7-3.1 Positive Peak Follower and Hold

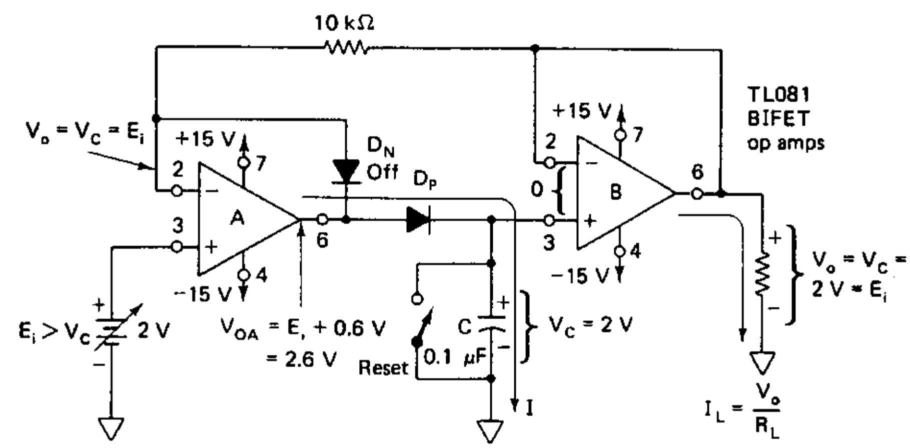
The peak *follower-and-hold* circuit is shown in Fig. 7-10. It consists of two op amps, two diodes, a resistor, a hold capacitor, and a reset switch. Op amp A is a precision half-wave rectifier that charges C only when input voltage E_i exceeds capacitor voltage V_C. Op amp B is a voltage follower whose output signal is equal to V_C. The follower's high input impedance does not allow the capacitor to discharge appreciably.

To analyze circuit operation, let us begin with Fig. 7-10(a). When E_i exceeds V_C, diode D_P is forward biased to charge hold capacitor C. As long as E_i is greater than V_C, C charges toward E_i. Consequently, V_C follows E_i as long as E_i exceeds V_C. When E_i drops below V_C, diode D_N turns on as shown in Fig. 7-10(b). Diode D_P turns off and disconnects C from the output of op amp A. Diode D_P must be a low-leakage-type diode or the capacitor voltage will discharge (droop). To minimize droop, op amp B should require small input bias currents (see Chapter 9). For that reason op amp B should be a metal-oxide-semiconductor (MOS) or bipolar-field-effect (BiFET) op amp.

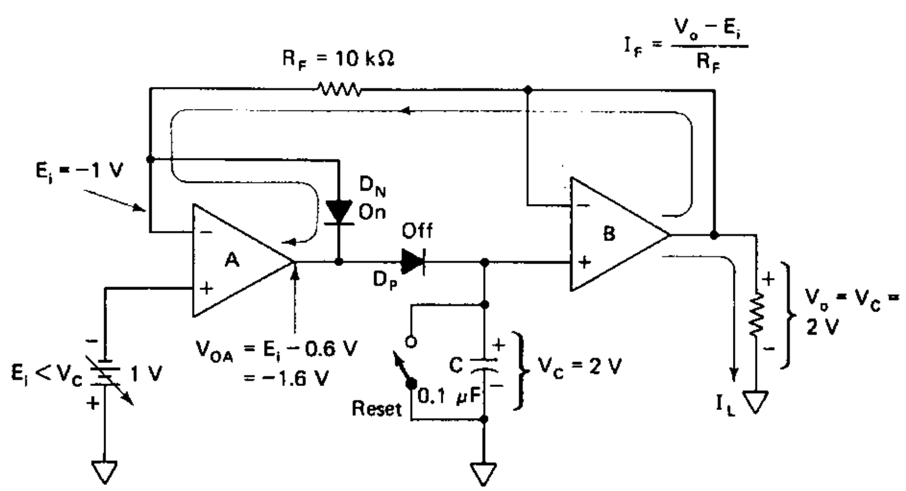
Figure 7-11 shows an example of voltage waveshapes for a positive voltage follower-and-hold circuit. To reset the hold capacitor voltage to zero, connect a discharge path across it with a 2-kΩ resistor.

7-3.2 Negative Peak Follower and Hold

When it is desired to hold the lowest or most negative voltage of a signal, reverse both diodes in Fig. 7-10. For bipolar or negative input signals, V_o will store the most negative voltage. It may be desired to monitor a positive voltage and catch any



(a) When E_i exceeds V_C, C is charged toward E_i via D_P



(b) When E_i is less than V_C, C holds its voltage at the highest previous value of E_i

Figure 7-10 Positive peak follower and hold or peak detector circuit. Op amps are TL081 BiFETs.

negative dips of short duration. Simply jumper a wire from V_C to the positive voltage to be monitored to load C with an equal positive voltage. Then when the monitored voltage drops and recovers, V_C will follow the drop and store the lowest value.

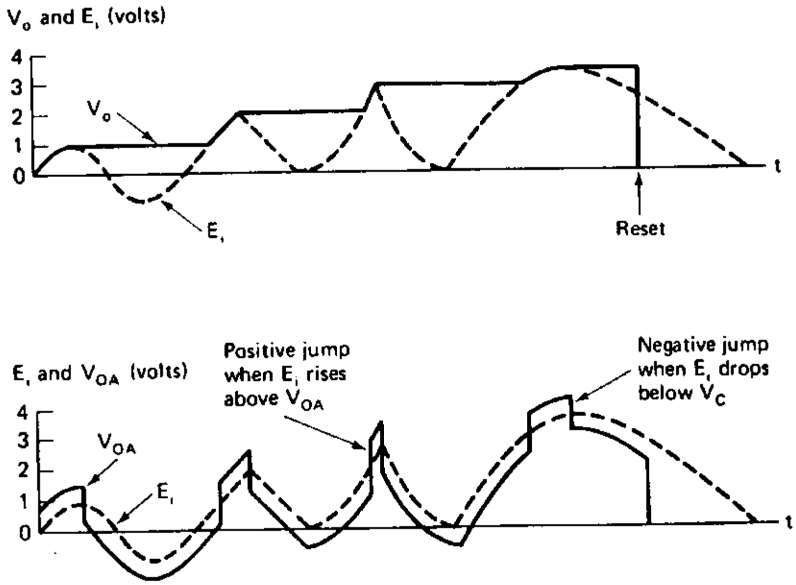


Figure 7-11 Waveshapes for the positive detector of Fig. 7-10(a).