

ECE 255, Diodes and Rectifiers

23 January 2018

In this lecture, we will discuss the use of Zener diode as voltage regulators, diode as rectifiers, and as clamping circuits.

1 Zener Diodes

In the reverse biased operation, a Zener diode displays a voltage breakdown where the current rapidly increases within a small range of voltage change. This property can be used to limit the voltage within a small range for a large range of current. The symbol for a Zener diode is shown in Figure 1.

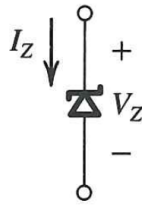


Figure 1: The symbol for a Zener diode under reverse biased (Courtesy of Sedra and Smith).

Figure 2 shows the $i-v$ relation of a Zener diode near its operating point where the diode is in the breakdown regime. The beginning of the breakdown point is labeled by the current I_{ZK} also called the **knee current**. The operating point can be approximated by an **incremental resistance**, or **dynamic resistance** described by the reciprocal of the slope of the point. Since the slope, proportional to $\frac{dI}{dV}$, is large, the incremental resistance is small, generally on the order of a few ohms to a few tens of ohms. The spec sheet usually gives the voltage of the diode at a specified test current I_{ZT} .

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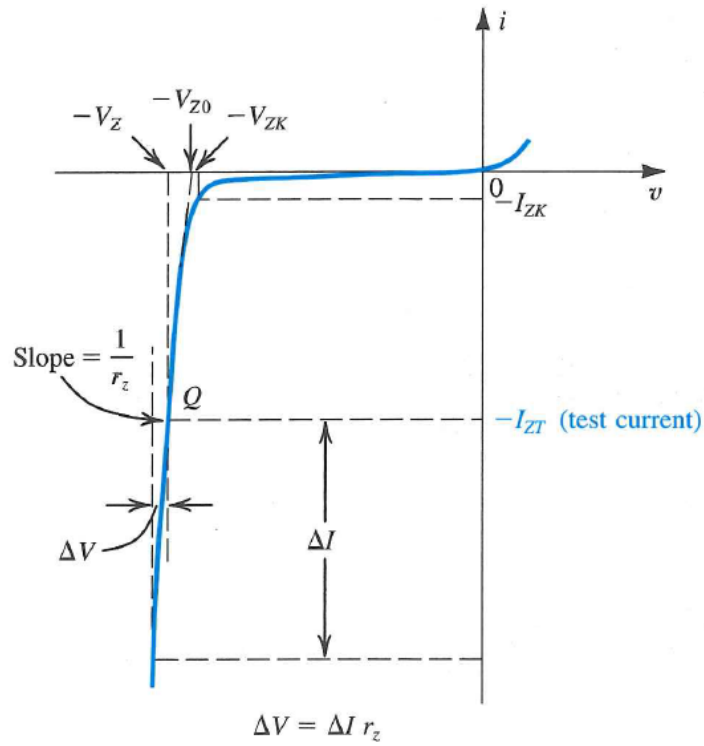


Figure 2: The i - v characteristic of a Zener diode at its operating point Q (Courtesy of Sedra and Smith).

The diode can be fabricated to have breakdown voltage of a few volts to a few hundred volts. When the operating point is fitted with a straight line, the point where the straight line touches the horizontal axis is known as V_{Z0} . Or

$$V_Z = V_{Z0} + r_Z I_Z \quad (1.1)$$

Around the operating point, the Zener diode can be approximated by a linear circuit model as shown in Figure 3

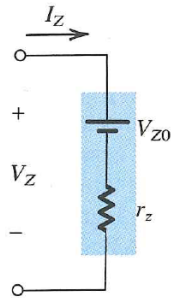


Figure 3: The Zener diode can be approximated by a linear circuit with an internal voltage source at its operating point (Courtesy of Sedra and Smith).

Figure 4 shows the use of the Zener diode as a shunt regulator. The circuit can be easily analyzed by linear circuit theory near its operating point.

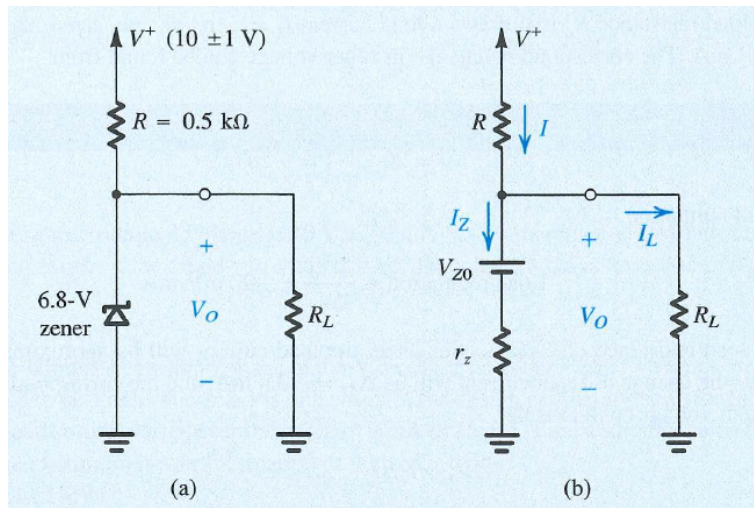


Figure 4: The use of the Zener diode as a shunt regulator (Courtesy of Sedra and Smith).

The breakdown voltage is often a function of temperature, and in the spec sheet, this is expressed in the of the **temperature coefficient**, which is in terms of $\text{mV}/^\circ\text{C}$).

2 Diodes as Rectifiers

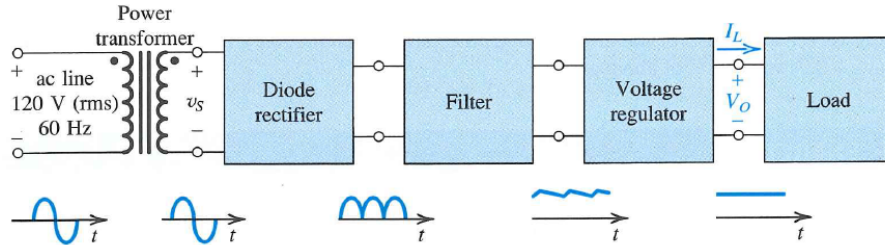


Figure 5: The use of diodes as a rectifier in a voltage regulator circuit (Courtesy of Sedra and Smith).

The most common and important applications of diodes is as rectifiers. In this mode, the diode converts an AC signal into a DC signal. The block diagram in Figure 5 shows the ideal use of the diodes. First, an ideal transformer (**power transformer**) converts the high AC voltage to some lower operating voltage, since most diodes operate in the low voltage regime. The step down voltage transformer works according to the formula that $V_2/V_1 = N_2/N_1$, where N_2/N_1 are the turn ratio of the transformer. Here, N_1 is the **primary winding** and N_2 is the **secondary winding**.

Then the ideal full-wave rectifier converts the AC voltage to become a unidirectional voltage waveform. This can be thought of a DC voltage with **ripples**. The ripples have higher frequency content, and can be removed by a low-pass filter. What that emerges after the filter is a smooth version of the rectified voltage signal. A voltage regulator can further smoothen this voltage signal before it is supplied to the load.

2.1 Half-Wave Rectifier

Figure 6 shows the simple use of diodes as a half-wave rectified. The PIV (peak inverse voltage) is the peak of the AC signal to be inverted. This is important to ensure that the PIV is not larger than the breakdown voltage of the diode, so that the diode can be approximated with an ideal diode with an internal voltage V_D . In this case, $PIV = V_s$. It is quite easy to show that the $v-i$ relation is $v_0 + v_D = v_s$ in the linear regime of the circuit when the diode turns on.

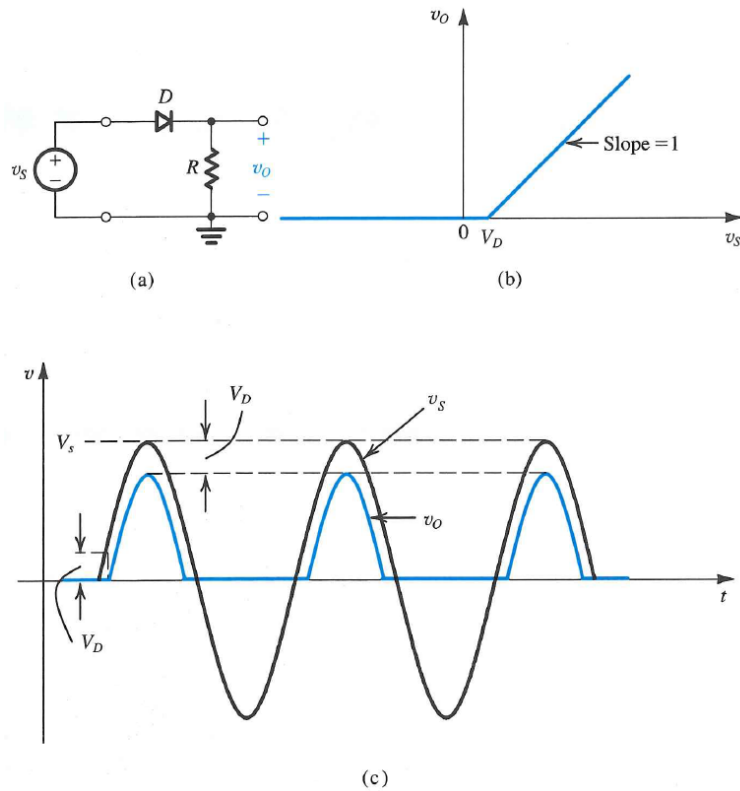


Figure 6: The use of the diode as a half-wave rectifier (Courtesy of Sedra and Smith).

2.2 Full-Wave Rectifier

The full-wave rectifier uses a **center tap** in the transformer circuit so that the two diodes are alternating in the forward and reverse biased mode. In this manner, there is always a positive current through the load irrespective of the sign of the AC voltage. Hence, the alternating direction AC current is converted to a unidirectional current, that has a DC component. This circuit is shown in Figure 7. In this case, the peak inverse voltage $PIV = 2V_s - V_D$, because when one of the diodes is in reverse bias, it receives voltage pressure from both the upper and the lower branches of the secondary winding.

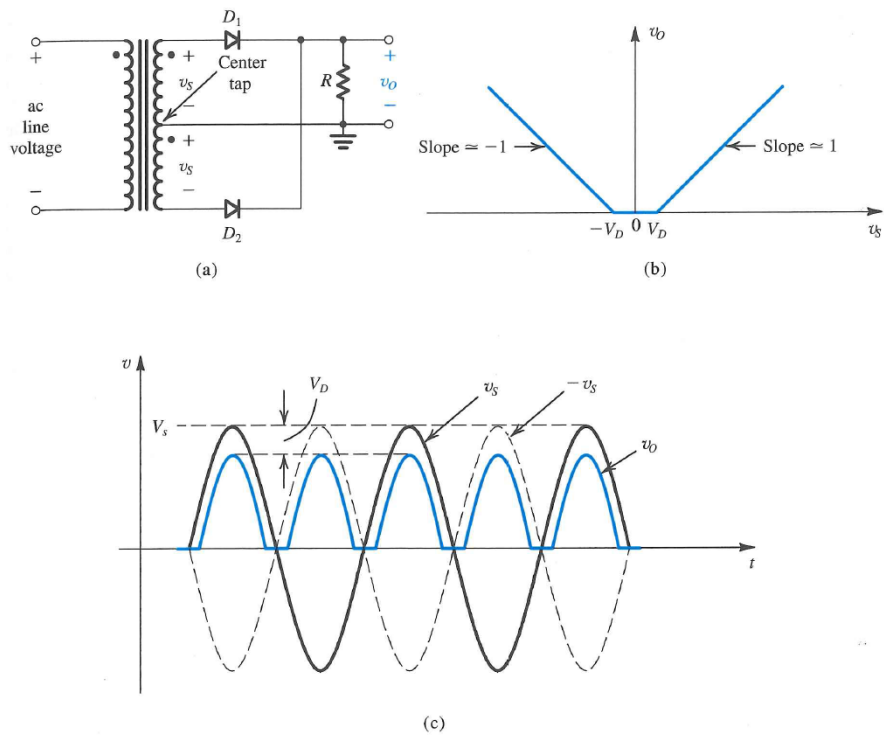


Figure 7: The use of the diode together with a center tap in the power transformer as a full-wave rectifier (Courtesy of Sedra and Smith).

Another way to make a full-wave rectifier is to use a bridge rectifier, also called the Wheatstone bridge rectifier. This is shown in Figure 8.

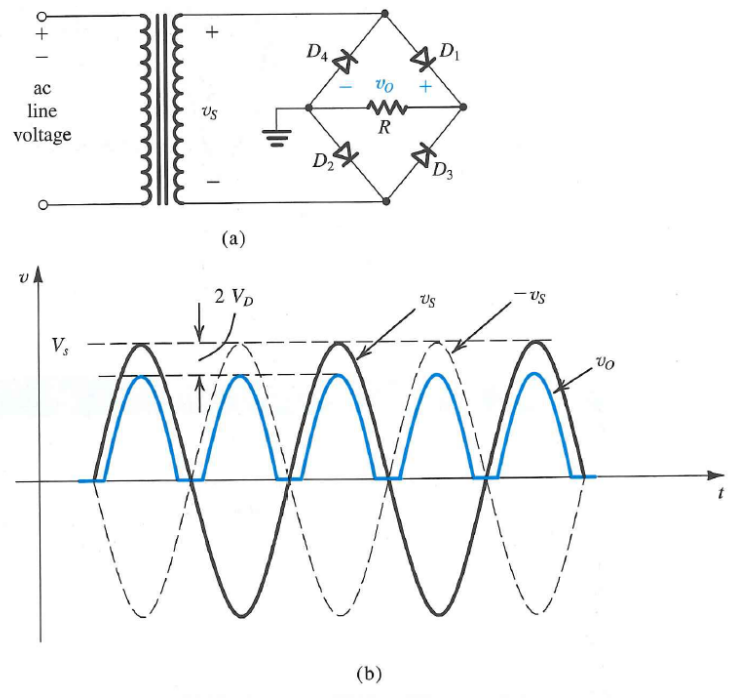


Figure 8: The use of the Wheatstone bridge as a full-wave rectifier (Courtesy of Sedra and Smith).

2.3 Smoothing the Current Ripple with a Capacitor

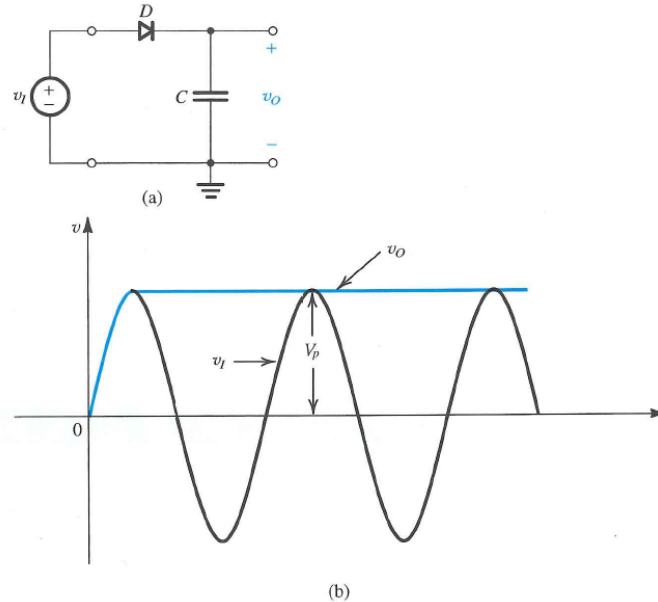


Figure 9: The capacitor alone hooked to a diode does not allow the discharge of the capacitor, and hence, the voltage across the capacitor remains constant once it is charged (Courtesy of Sedra and Smith).

Since a capacitor is a charge storage device, it can be used to store strong currents as charges during its positive strong current cycle, and release the stored charges as currents during the low current cycle. In this manner, the current flow can be smoothed. These capacitors are known as **filtered capacitors**.

First, we show the case in Figure 9, where the ideal capacitor is hooked to the diode that rectifies the voltage source. However, the ideal capacitor does not have a chance to discharge. Hence, the voltage across the capacitor remains constant once it is charged. But this case is not practical or real as a capacitor leaks its charge eventually. Also, one needs to hook the rectified voltage source to a load.

The use of the capacitor to smooth a half-wave rectifier is shown in Figure 10. Its use in smoothing the current for full-wave rectifier is shown in Figure 11. Though the physics or the physical mechanism for current smoothing is quite easy to understand, its math is a bit more complicated.

First, let us consider a resistor connected to a capacitor, as shown in Figure 10(a). The capacitor will charge and discharge according to the equation

$$i_D = i_C + i_L = C \frac{dv_o}{dt} + \frac{v_o}{R} \quad (2.1)$$

Discharging case:

One assumes that the circuit has been running over many cycles so that it has reached a steady state of charging and discharging. Between $t_2 < t < T - \Delta t$ in Figure 10(a), $v_0 > v_I$ and hence, the diode is off. When the diode is off or $i_D = 0$, the solution to this equation is of the form

$$v_0 = V_p e^{-t/(RC)} \quad (2.2)$$

Therefore, at the end of the discharge interval, $t \approx T$, and

$$v_0 = V_p - V_r \approx V_p e^{-T/(RC)} \quad (2.3)$$

where V_r is the **ripple voltage**. For $RC \gg T$, $e^{-T/(RC)} \approx 1 - T/(RC)$, yielding

$$V_r \approx V_p \frac{T}{RC} \quad (2.4)$$

Using that $f = 1/T$, the above can be rewritten as

$$V_r = \frac{V_p}{fRC} = \frac{I_L}{fC} \quad (2.5)$$

where one assumes that $I_L \approx \frac{V_p}{R}$ is the DC current through the load. It is seen that in order for the ripple voltage V_r to be small, for a constant load current I_L , the capacitor has to be large, and the frequency has to be high. Alternatively, R has to be large, or I_L has to be small.

Charging case:

Referring to the same figure, when $T - \Delta t < t < T$, $v_I > v_0$ and the diode turns on. The capacitor is now being charged. The charging or conduction interval can be estimated by letting

$$V_p \cos(\omega \Delta t) = V_p - V_r \quad (2.6)$$

where $\omega = 2\pi f = 2\pi/T$. Assuming that $\omega \Delta t$ is small, then $\cos(\omega \Delta t) \approx 1 - \frac{1}{2}(\omega \Delta t)^2$. The quadratic equation in $\omega \Delta t$ can be solved to yield

$$\omega \Delta t \approx \sqrt{2V_r/V_p} \quad (2.7)$$

To find the diode current during the conduction interval, it is noted that

$$Q_{\text{supplied}} = i_{C\text{av}} \Delta t = Q_{\text{lost}} = C(V_p - V_{\text{min}}) = CV_r \quad (2.8)$$

But from KCL,

$$i_{D\text{av}} = i_{C\text{av}} + I_L \quad (2.9)$$

From (2.8), one notices that $i_{C\text{av}} = \frac{CV_r}{\Delta t}$. Furthermore, using (2.5), then (2.9) becomes

$$i_{D\text{av}} = \frac{CV_r}{\Delta t} + I_L = \frac{I_L}{f\Delta t} + I_L = I_L \left(1 + \frac{1}{f\Delta t} \right) = I_L \left(1 + \pi \sqrt{2V_p/V_r} \right) \quad (2.10)$$

where (2.7) has been used to find Δt . It is seen that $i_{D\text{av}}$ is large when the ripple voltage is small or that $V_r/V_p \ll 1$. Furthermore, when the ripple is small, then $i_{D\text{max}} \approx 2i_{D\text{av}}$.

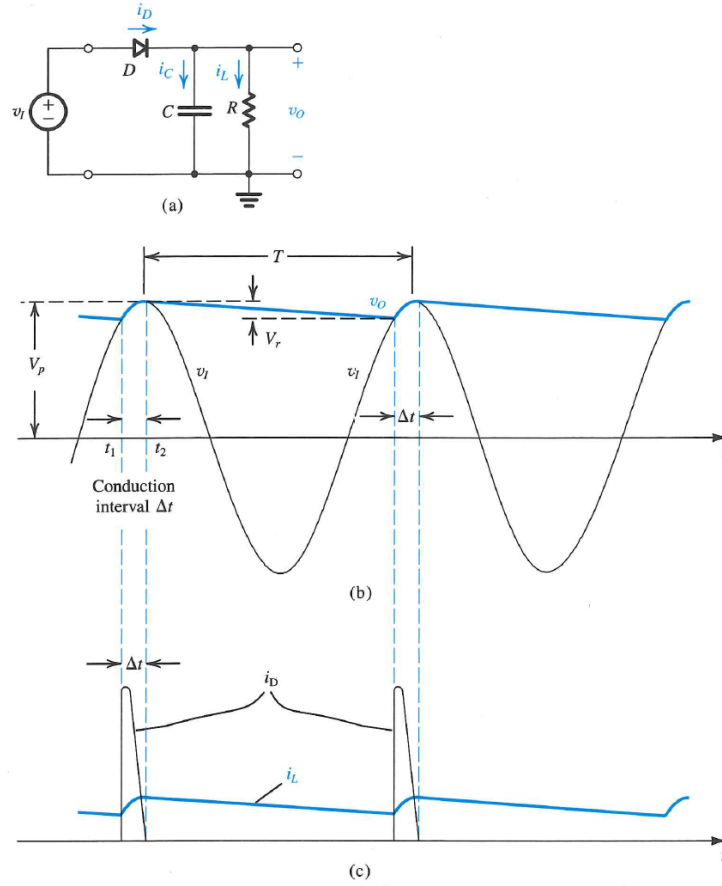


Figure 10: The use of a capacitor as a current smoother in the half-wave rectifier circuit (Courtesy of Sedra and Smith).

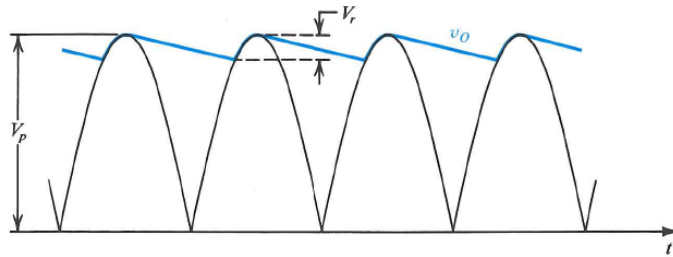


Figure 11: The use of a capacitor as a current smoother in the full-wave rectifier circuit (Courtesy of Sedra and Smith).

3 A Voltage Clamping or Limiter Circuit

A voltage clamping or limiter circuit can be used to limit the output voltage of a circuit when the input voltage is too large. The output voltage with respect to the input voltage plot is shown in Figure 12. This is the case of an ideal clamping circuit. In practice, a less ideal one will be achieved as shown in Figure 13.

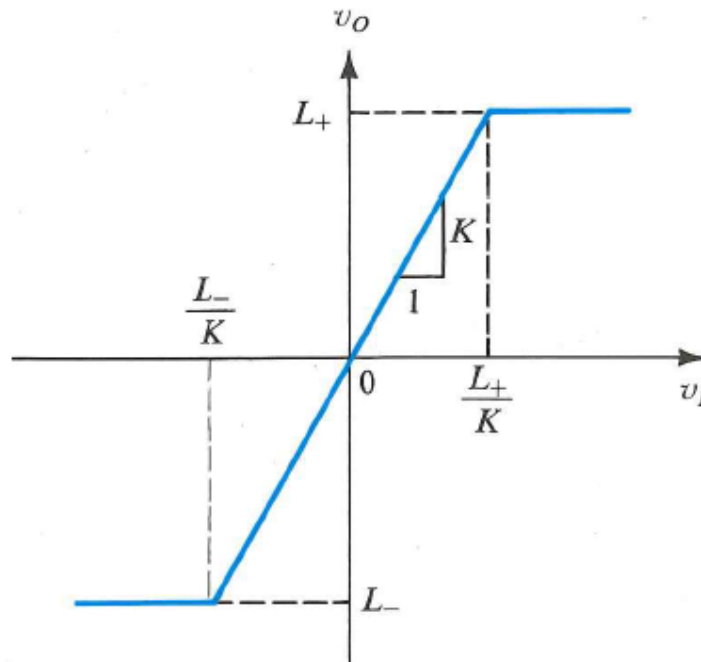


Figure 12: An ideal clamping or limiter circuit (Courtesy of Sedra and Smith).

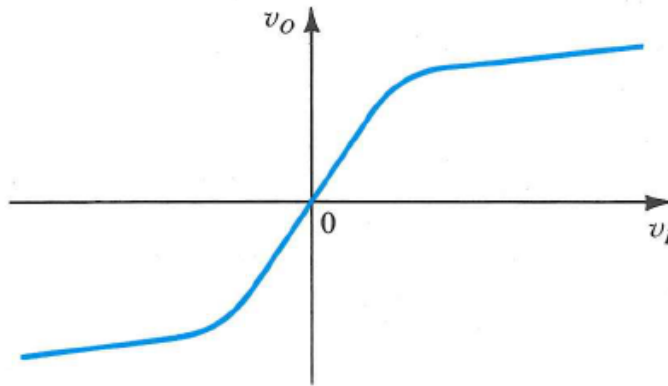


Figure 13: An less ideal clamping or limiter circuit in practice (Courtesy of Sedra and Smith).

Figure 14 shows the use of ideal limiting circuit to clip off the peak voltage of an AC signal.

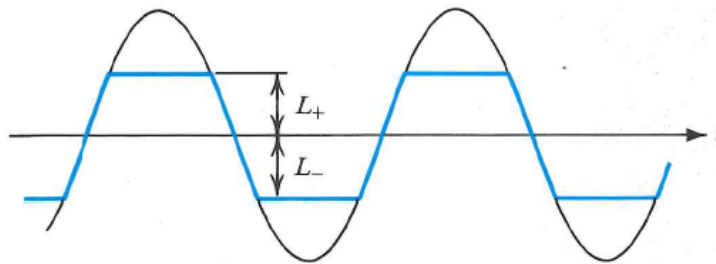


Figure 14: An ideal clamping or limiter circuit used to clip off the voltage peaks of an AC signal (Courtesy of Sedra and Smith).

Figure 15 shows the principle and some practical designs of limiting circuits. While a simple diode limits the voltage to the turn-on voltage of 0.7 V, the use of Zener diode can clamp the voltage to a large range of voltages from several volts to several hundred volts. This is achieved by fabricating Zener diodes with different breakdown voltages.

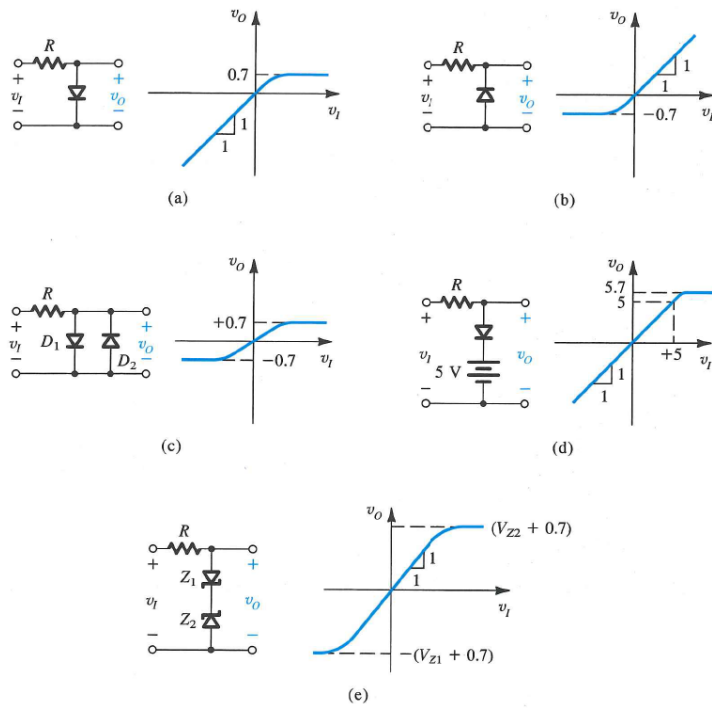


Figure 15: The operating principles and designs of clamping circuits (Courtesy of Sedra and Smith).