TECHNICAL UNIVERSITY OF KOŠICE

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATICS

DEPARTMENT OF ELECTRONICS AND MULTIMEDIA COMMUNICATIONS

BASIC OF ELECTRONICS

Lecture 2

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Applied Informatics

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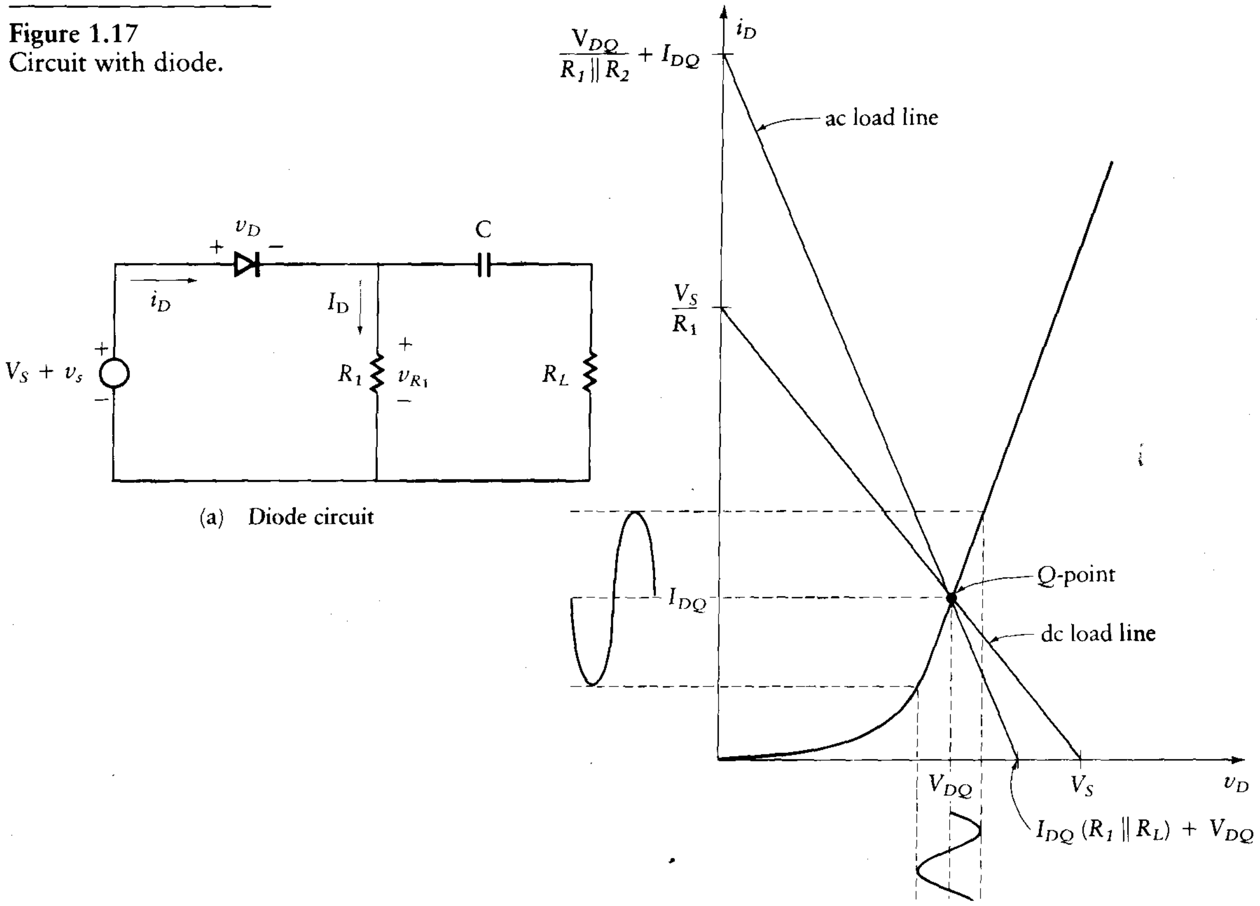
Figure 1.17
Circuit with diode.



(a) Diode circuit

(b) Diode load lines

A circuit often contains both dc supply voltages and time-varying sources. If we set the time-varying sources equal to zero, the only energy supplied to the circuit comes from the dc supply voltages. With the time-varying sources out of the circuit, the diode voltage and current define what is known as the *quiescent operating point (Q-point)*.

Figure 1.17(a) illustrates a circuit with a diode, capacitor, source, and two resistors. If we designate the diode current and diode voltage as the two circuit unknowns, we need two independent equations involving these unknowns in order to find a unique solution for the operating point. One of the equations is the constraint provided by the circuitry connected to the diode. The second is the actual diode voltage-current relationship. These two equations must be simultaneously solved to yield the diode voltage and current. This simultaneous solution can be done graphically.

If we first look at the dc condition, the voltage source becomes simply V_S, and the capacitor is an open circuit (i.e., the impedance of the capacitor is infinity at a frequency of zero). Thus, the loop equation can be written as

$$V_S = V_D + V_{R1} = V_D + I_D R_1$$

or

$$V_D = -R_1 I_D + V_S \tag{1.6}$$

This is the first of two simultaneous equations involving the diode voltage and current. We need to combine this with the diode characteristic in order to solve for the operating point. The graph of this equation is shown in Figure 1.17(b) and is labeled "dc load line." The graph of the diode characteristic is also shown on this same set of axes. The intersection of the two plots yields the simultaneous solution of the two equations and is labeled "Q-point" on the figure. This is the point at which the circuit will operate with the time-varying inputs set to zero. The Q denotes the "quiescent," or rest, condition.

If a time-varying signal is now applied in addition to the dc input, one of the two simultaneous equations changes. If we assume that the time-varying input is of a high-enough frequency to allow approximation of the capacitor as a short circuit, the new equation is given by equation (1.7):

$$v_s = v_d + i_d(R_1 \parallel R_L)$$

or

$$v_d = -(R_1 \parallel R_L) i_d + v_s \tag{1.7}$$

We are considering only the time-varying components of the various parameters. (Note the use of lowercase letters for the variables. Refer to the labeling convention presented at the beginning of this text.) Thus, the total parameter values are given by

$$v_D = v_d + V_{DQ}$$

$$i_D = i_d + I_{DQ}$$

and equation (1.7) becomes

$$v_D - V_{DQ} = -(R_1 \parallel R_L)(i_D - I_{DQ}) + v_s$$

This last equation is labeled "ac load line" in Figure 1.17(b). The ac load line must pass through the Q-point, since at those times when the time-varying part of the input goes to zero, the two operating conditions (dc and ac) must coincide. Thus, the ac load line is uniquely determined.

Example 1.1

The source voltage,

$$v_S = 1.1 + 0.1 \sin 1000t$$

is placed across a series combination of a diode and a 100 Ω load resistance, as shown in Figure 1.18. Find the current, i_D, if

$$nV_T = 40 \text{ mV}$$

$$V\gamma = 0.7 \text{ V}$$

SOLUTION We use KVL for the dc equation to yield

$$V_S = V\gamma + I_D R_L$$

$$I_D = \frac{V_S - V\gamma}{R_L} = \frac{1.1 - 0.7}{100} = 4 \text{ mA}$$

This sets the dc operating point of the diode. We need to determine the dynamic resistance (we use the symbol R_f instead of r_d, since it includes the contact resistance) so we can establish the resistance of the forward-biased junction for the ac signal.

Using equation (1.4a) and assuming that the contact resistance is negligible, we have

$$R_f = \frac{nV_T}{I_D} = \frac{40 \text{ mV}}{4 \text{ mA}} = \mathbf{10\ \Omega}$$

Now we can replace the diode with a 10 Ω resistor, provided it remains forward-biased during the entire period of the input ac signal. Again using KVL, we have

$$v_s = R_f i_d + R_L i_d$$

$$i_d = \frac{v_s}{R_f + R_L} = \frac{0.1 \sin 1000t}{110} = 0.91 \sin 1000t \text{ mA}$$

The diode current is then given by

$$i_D = 4 + 0.91 \sin 1000t \text{ mA}$$

Since i_D is always positive the diode is always forward-biased, and the solution is complete.

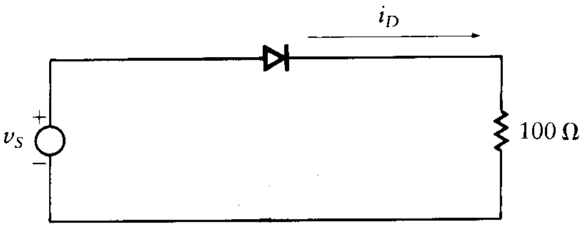


Figure 1.18
Diode series circuit.

If the ac current amplitude becomes greater than the dc current value, the solution must be modified. In that case, when the ac current amplitude in the negative direction becomes larger than the dc value, the diode becomes reverse-biased and the current is cut off. This case is covered in Section 1.8. ▶

1.3.5 *Power-Handling Capability*

Diodes are rated according to their power-handling capability. The ratings are determined by the physical construction of the diode (e.g., size of junction, type of packaging, and size of diode). The manufacturer's specifications are used to determine the power capability of a diode for certain temperature ranges. Some diodes, such as power diodes, are rated by their current-carrying current-carrying capacity.

The instantaneous power dissipated by a diode is defined by the expression in equation (1.8):

$$p_D = v_D i_D \tag{1.8}$$

1.3.6 *Diode Capacitance*

The equivalent circuit of a diode includes a small capacitor. The size of this capacitor depends upon the magnitude and polarity of the voltage applied to the diode as well as upon the characteristics of the junction formed during manufacture.

In the simple model of a diode junction shown in Figure 1.19, the region at the junction is depleted of both electrons and holes. On the *p*-side of the junction, there is a high concentration of holes, and on the *n*-side of the junction, there is a high concentration of electrons. Diffusion of these electrons and holes occurs close to the junction, causing an initial *diffusion current.* When the holes diffuse across the junction into the *n*-region, they quickly combine with the majority electrons present in that area and disappear. Likewise, electrons also diffuse across the junction, recombine, and disappear. This causes a *depletion region* (sometimes called the *space charge region*) near the junction due to the recombination of electrons and holes. As a reverse voltage is applied across the junction, this region widens, causing the depletion region to increase in size.

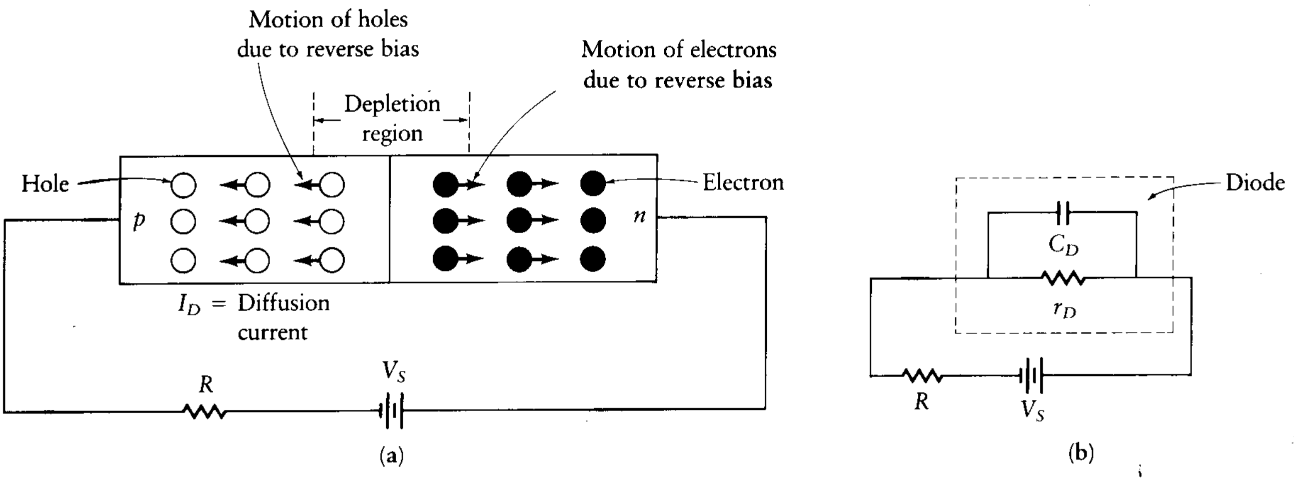


Figure 1.19 Diode model and equivalent circuit.

The depletion region acts like an insulator. Thus, a reverse-biased diode acts like a capacitor whose capacitance varies inversely with the square root of the voltage drop across the semiconductor material.

The equivalent capacitance for high-speed diodes is less than 5 pF. This capacitance can become as large as 500 pF in high-current (low-speed) diodes. The manufacturer's specifications should be consulted to determine the anticipated amount of capacitance for a given operating condition.

1.4 Rectification

We are now ready to see how the diode is configured to perform a useful function. The first major application we consider is that of *rectification.*

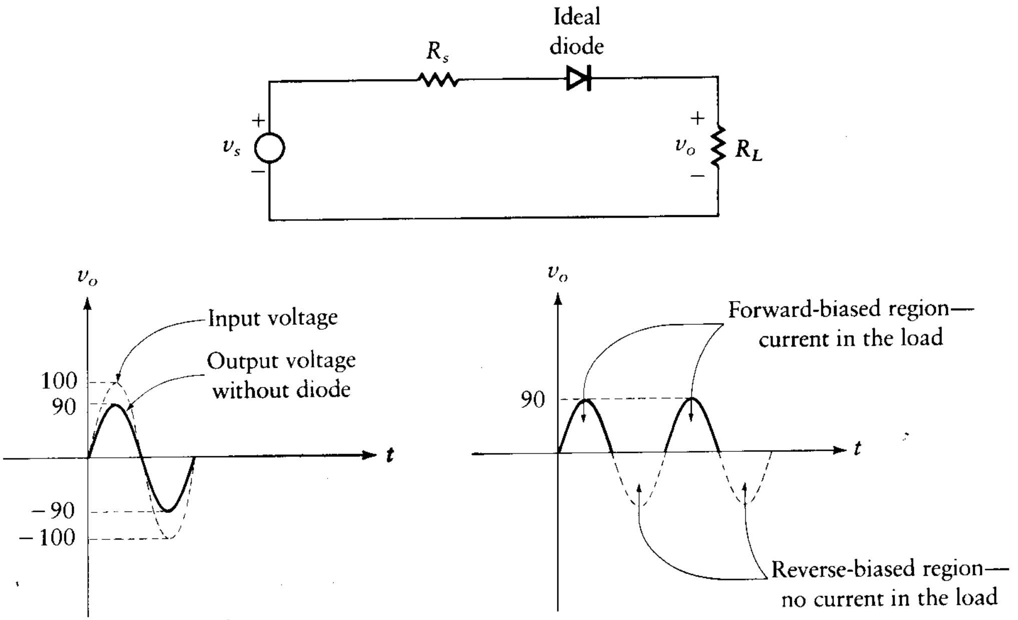
Rectification is the process of turning an alternating signal (ac) into one that is restricted to only one direction (dc). Rectification is classified as either *half-wave* or *full-wave.*

1.4.1 *Half-Wave Rectification*

Since an ideal diode can sustain current flow in only **one direction, it can be** used to change an ac signal into a dc signal.

Figure 1.20 illustrates a simple *half-wave rectifier* circuit. When the input voltage is positive, the diode is forward-biased and can be replaced (assume it is ideal) by a short circuit. When the input voltage is negative, the diode is reverse-biased and can be replaced by an open circuit (provided the voltage

Figure 1.20
Half-wave rectifier.



does not get sufficiently negative to break down the diode). Thus, when the diode is forward-biased, the output voltage across the load resistor can be found from the voltage divider relationship. Alternatively, in the reverse-biased condition, the current is zero, so the output voltage is also zero.

Figure 1.20 shows an example of the output waveform assuming a 100 V amplitude sinusoidal input, $R_s = 10\ \Omega$, and $R_L = 90\ \Omega$.

The half-wave rectifier can be used to create an almost-constant dc output if the resulting waveform of Figure 1.20 is filtered. The filtering operation is discussed in Section 1.4.3. We note that the half-wave rectifier is not very efficient. During one-half of each cycle, the input is completely blocked from the output. If we could transfer input energy to the output during this half-cycle, we would increase output power for a given input.

1.4.2 *Full-Wave Rectification*

A *full-wave rectifier* transfers input energy to the output during both halves of the cycle and provides increased average current per cycle over that obtained using the half-wave rectifier. A transformer is usually used in constructing a full-wave rectifier in order to obtain the positive and negative polarities. A representative circuit and the output voltage curve are shown in Figure 1.21.

The *average* of a periodic function is defined as the integral of the function over one period divided by the period. It is equal to the first term in a Fourier series expansion of the function. The full-wave rectifier produces *twice* the average current of that of the half-wave rectifier. (You should verify this statement.)

Figure 1.21
Full-wave rectifier.

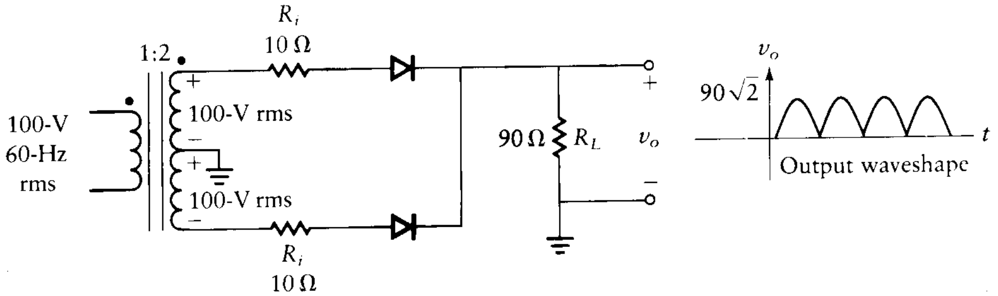


Figure 1.22
Full-wave bridge rectifier.

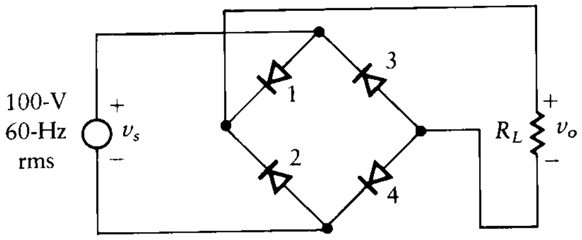
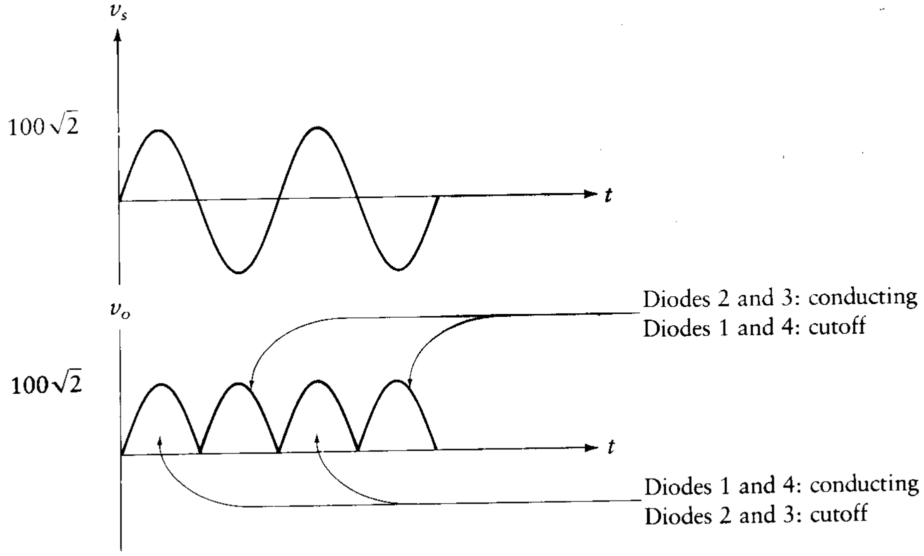


Figure 1.23
Bridge rectifier-diode conduction times.



Full-wave rectification is possible without the use of a transformer. The *bridge rectifier* of Figure 1.22 accomplishes full-wave rectification. When the source voltage is positive, diodes 1 and 4 conduct and diodes 2 and 3 are open circuit. When the source voltage goes negative, the reverse situation occurs, and diodes 2 and 3 conduct. This is indicated in Figure 1.23. Study of Figure 1.22 indicates a possible practical shortcoming of the bridge rectifier circuit. If one terminal of the source is grounded, neither terminal of the load resistor can be grounded. To do so would cause a *ground loop*, which would effectively short out one of the diodes. Therefore, it may be necessary to add a transformer to this circuit in order to isolate the two grounds from each other.

1.6 Zener Diodes

A *zener diode* is a device where the doping is performed in such a way as to make the *avalanche* or *breakdown* voltage, V_Z, characteristic very steep. If the reverse voltage exceeds the breakdown voltage, the diode normally will not be destroyed. This is true as long as the current does not exceed a predetermined maximum and the device does not overheat.

When a thermally generated carrier (part of the reverse saturation current) falls down the junction barrier (see Figure 1.14) and acquires energy of the applied potential, the carrier collides with crystal ions and imparts sufficient energy to disrupt a covalent bond. In addition to the original carrier, a new electron-hole pair is generated, which may pick up sufficient energy from the applied field to collide with another crystal ion and create still another electron-hole pair. This action continues and thereby disrupts the covalent bonds; the process is referred to as *avalanche multiplication* or *avalanche breakdown.*

There is a second mechanism that disrupts the covalent bonds. The use of a sufficiently strong electric field at the junction can cause a direct rupture of the bond. If the electric field exerts a strong force on a bound electron, the electron can be torn from the covalent bond thus causing the electron-hole pair combination to multiply. This mechanism is called *zener breakdown.* The value of reverse voltage at which this phenomenon occurs is controlled by the amount of doping of the diode. A heavily doped diode has a low zener breakdown voltage, whereas a lightly doped diode has a high zener breakdown voltage.

Although we describe two distinctly different mechanisms to effect breakdown, they are commonly interchanged. At voltages above approximately 10 V, the mechanism most predominant is the avalanche breakdown ([35], Section 2.9). Since the zener effect (avalanche) occurs at a predictable point, the diode can be used as a voltage reference. The reverse voltage at which the avalanche occurs is called the *zener voltage.*

A typical zener diode characteristic is shown in Figure 1.28. The circuit symbol for the zener diode is different from that of a regular diode and is illustrated in Figure 1.28.

The maximum reverse current, $I_{Z\,\text{max}}$, that the zener diode can withstand is dependent upon the design and construction of the diode. The leakage current ($I_{Z\,\text{min}}$) below the knee of the characteristic curve is usually assumed to be $0.1 I_{Z\,\text{max}}$. Use of $I_{Z\,\text{min}}$ assures that the avalanche curve remains parallel to the i_D axis between $I_{Z\,\text{max}}$ and $I_{Z\,\text{min}}$. The amount of power that the zener diode can withstand is $P_Z = I_{Z\,\text{max}} V_Z$.

1.6.1 *Zener Regulator*

A zener diode can be used as a voltage regulator in the configuration shown in Figure 1.29. The figure illustrates a load with resistance that can vary over a particular range. The circuit is designed so that the diode operates in the breakdown region, thereby approximating an ideal voltage source. The output voltage remains relatively constant even when the input source voltage varies over a relatively wide range ([49], Section 4.4).

Figure 1.28
Zener diode.

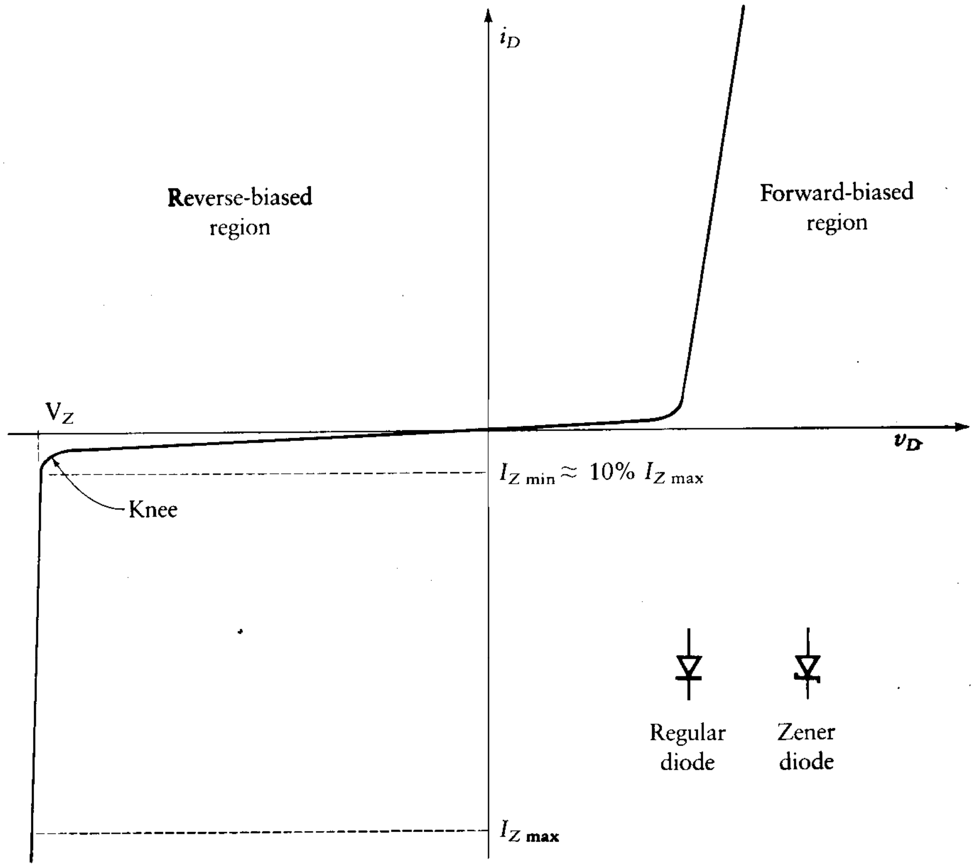
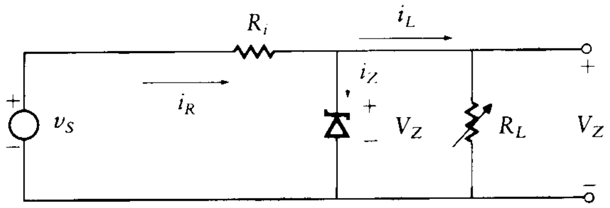


Figure 1.29
Zener regulator.



It is important to know the range of input voltage and load current in order to properly design this circuit. The resistance, R_i, must be such that the diode stays in the constant voltage mode over the entire range of variables.

The node equation for the circuit of Figure 1.29 yields

$$R_i = \frac{v_S - V_Z}{i_R} = \frac{v_S - V_Z}{i_Z + i_L} \tag{1.12}$$

In order to assure that the diode remains in the constant voltage (breakdown) region, we examine the two extremes of input/output conditions.

1. The current through the diode i_Z is a minimum when the load current i_L is maximum and the source voltage v_S is minimum.
2. The current through the diode i_Z is a maximum when the load current i_L is minimum and the source voltage v_S is maximum.

When these characteristics of the two extremes are inserted into equation (1.12), we find

$$\text{Condition 1:} \quad R_i = \frac{V_{S\,\min} - V_Z}{I_{L\,\max} + I_{Z\,\min}} \tag{1.13a}$$

$$\text{Condition 2:} \quad R_i = \frac{V_{S\,\max} - V_Z}{I_{L\,\min} + I_{Z\,\max}} \tag{1.13b}$$

We equate (1.13a) and (1.13b) to obtain

$$(V_{S\,\min} - V_Z)(I_{L\,\min} + I_{Z\,\max}) = (V_{S\,\max} - V_Z)(I_{L\,\max} + I_{Z\,\min}) \tag{1.13c}$$

In a practical problem, it is reasonable to assume that we know the range of input voltages, the range of output load currents, and the desired zener voltage. Equation (1.13c) thus represents one equation in two unknowns, the maximum and minimum zener current. A second equation is found by examining Figure 1.28. In order to avoid the nonconstant portion of the characteristic curve, we use a rule of thumb that the maximum zener current should be 10 times the minimum ([46], Section 5.4); that is,

$$I_{Z\,\min} = 0.1 I_{Z\,\max}$$

This is an accepted design criterion.

We now rewrite equation (1.13c) as

$$(V_{S\,\min} - V_Z)(I_{L\,\min} + I_{Z\,\max}) = (V_{S\,\max} - V_Z)(I_{L\,\max} + 0.1 I_{Z\,\max})$$

Then solving for the maximum zener current, we obtain

$$I_{Z\,\max} = \frac{I_{L\,\min}(V_Z - V_{S\,\min}) + I_{L\,\max}(V_{S\,\max} - V_Z)}{V_{S\,\min} - 0.9 V_Z - 0.1 V_{S\,\max}} \tag{1.14}$$

Now that we can solve for the maximum zener current, the value of R_i is calculated from either equation (1.13a) or equation (1.13b).

Example 1.2 Zener Regulator Design

Design a zener regulator (Figure 1.30) for each of the following conditions:

a. The load current ranges from 100 mA to 200 mA and the source voltage ranges from 14 V to 20 V.

b. The load current ranges from 20 mA to 200 mA and the source voltage ranges from 10.2 V to 14 V.

Use a 10-V zener diode in both cases.

SOLUTION

a. The design consists of choosing the proper value of resistance, R_i, and power rating for the zener. We use the equations from this section first to calculate the maximum current in the zener diode and then to find the input resistor value. From equation (1.14), we have

$$I_{Z\,\max} = \frac{0.1(10 - 14) + 0.2(20 - 10)}{14 - 0.9(10) - 0.1(20)}$$

$$= \frac{1.6}{3} = 0.533 \text{ A}$$

Then, from equation (1.13b), we find R_i as follows:

$$R_i = \frac{V_{S\,\max} - V_Z}{I_{Z\,\max} + I_{L\,\min}} = \frac{20 - 10}{0.533 + 0.1} = 15.8\ \Omega$$

It is not sufficient to specify only the resistance of R_i. We must also select the proper resistor power rating. The maximum power is given by the product of voltage and current, where we use the maximum for each value.

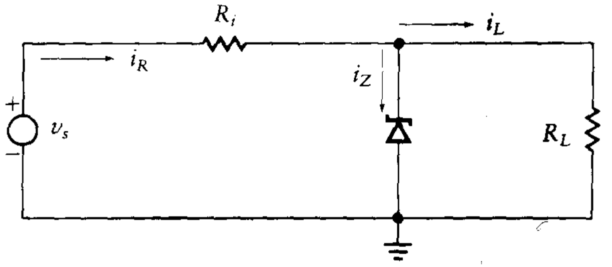
$$P_R = I_{R\,\max}(V_{S\,\max} - V_Z)$$

$$= (I_{Z\,\max} + I_{L\,\min})(V_{S\,\max} - V_Z)$$

$$= 0.63 \times 10 = 6.3 \text{ W}$$

;ure 1.30

ner diode regulator.



Finally, we must determine the power rating of the zener diode. The maximum power dissipated in the zener diode is given by the product of voltage and current.

$$P_Z = V_Z I_{Z\,\max} = 10 \times 0.53 = 5.3\text{ W}$$

b. Repeating these steps for the parameters of part (b) yields

$$I_{Z\,\max} = \frac{0.02(10 - 10.2) + 0.2(14 - 10)}{10.2 - 0.9(10) - 0.1(14)} = -4\text{ A}$$

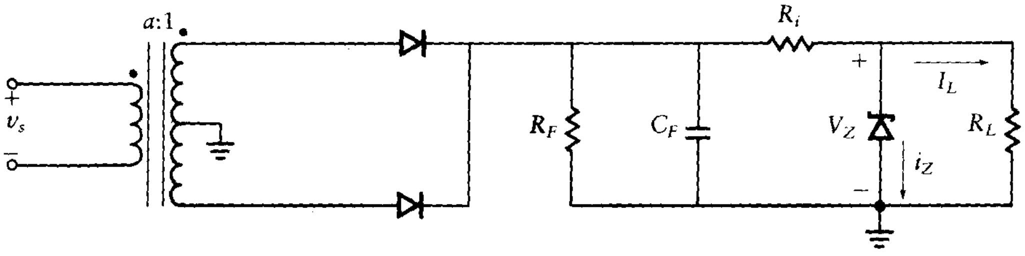
The negative value of $I_{Z\,\max}$ indicates that the margin between $V_{S\,\min}$ and V_Z is not large enough to allow for the variation in load current. That is, under the worst case condition of a 10.2 V input and 200 mA load current, the zener cannot possibly sustain 10 V across its terminals. Therefore, the regulator will not operate correctly for any choice of resistance. ▶

The zener regulator circuit of Figure 1.30 can be combined with the full-wave rectifier of Figure 1.24 to yield the full-wave zener regulator of Figure 1.31.

The component R_F is called a *bleeder resistor* and is used to provide a discharge path for the capacitor when the load is removed. Bleeder resistors are normally high resistances in order not to absorb significant power when the circuit is operating. Since R_F is much larger than R_i, we neglect it in the following analysis.

The value of C_F is found by adapting equation (1.10) to this situation. The resistance in the equation is the equivalent resistance across C_F. The zener diode is replaced by a voltage source, V_Z. The equivalent resistance is then the parallel combination of R_F with R_i. Since R_F is much larger than R_i, the resistance is approximately equal to R_i. Since the voltage across R_i does not go to zero, as is the case for the full-wave rectifier, $V_{\max}$ in equation (1.9) must be replaced by the total voltage swing. Thus, the capacitor is as specified in equation (1.15), where we are assuming a (the transformer ratio) is 1.

Figure 1.31 Full-wave zener regulator.



$$C_F = \frac{5(V_{S\,\max} - V_Z)}{\Delta V 2\pi f_p R_i} \tag{1.15}$$

The largest voltage imposed upon the regulator is $V_{S\,\max}$. As before, ΔV is the peak-to-peak ripple and f_p is the fundamental frequency of the rectified waveform (i.e., twice the original frequency for full-wave rectification).

1.6.2 *Practical Zener Diodes and Percent Regulation*

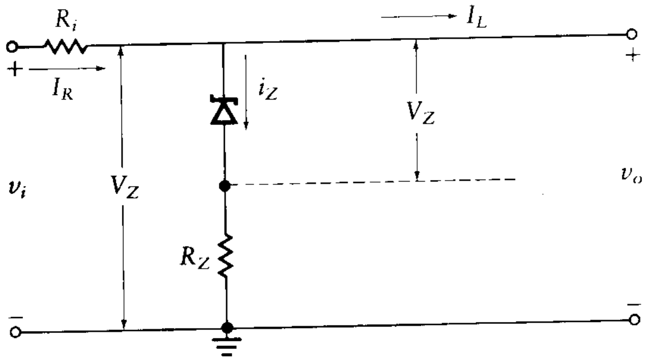
In the previous section we assumed that the zener diode was ideal. That is, in the avalanche breakdown region, the diode behaves as a constant voltage source. This assumption means that the curve of Figure 1.28 is a vertical line in the breakdown region. In practice, this curve is not vertical, and the slope is caused by a series resistance. The breakdown voltage is then a function of current instead of being a constant. We model the practical zener diode as shown in Figure 1.32. This model replaces the practical zener diode with an ideal diode in series with a resistance, R_Z.

In order to show the effects of this series resistor, we once again solve Example 1.2. We assume that a practical zener diode is incorporated into the circuit, with the diode resistance $R_Z = 2\ \Omega$. In that example, the circuit of Figure 1.30 is used as a regulator where the maximum zener current is 0.53 A. We assume that $I_{Z\,\min}$ is 10% of $I_{Z\,\max}$, or 0.053 A. The output voltage (across the load) is no longer a constant 10 V because of R_Z. We find the minimum and maximum values of this voltage from Figure 1.32 using the minimum and maximum current values. The voltage across the ideal diode of Figure 1.32 is 10 V, so we can write

$$V_{o\,\min} = 10 + (0.053 \times 2) = 10.1\ \text{V}$$

$$V_{o\,\max} = 10 + (0.53 \times 2) = 11.1\ \text{V}$$

Figure 1.32 Zener equivalent circuit.



The *percent regulation* is defined as the total voltage swing divided by the nominal voltage. The smaller the percent regulation, the better the regulator. Therefore, for this example,

$$\text{percent reg.} = \frac{V_{o\,\max} - V_{o\,\min}}{V_{o\,\text{nominal}}} = \frac{11.1 - 10.1}{10}$$

$$= 0.1, \text{ or } 10\% \qquad (1.16)$$

This value of regulation is poor and the regulation can be improved by limiting the zener current to a smaller value. This is accomplished by using an amplifier in series with the load. The effect of this amplifier is to limit the variations of current through the zener diode. We study such amplifiers in Chapter 6.

Drill Problems

D1.9 A zener diode regulator circuit (see Figure 1.30) has an input whose voltage varies between 10 and 15 V and a load whose current varies between 100 mA and 500 mA. Find the values of R_i and $I_{Z\,\max}$ assuming that a 6 V zener is used.

Ans: 6.33 Ω; 1.32 A

D1.10 In Problem D1.9, find the power ratings for the zener diode and for the input resistor.

Ans: 7.94 W; 12.8 W

D1.11 In Problem D1.9, find the value of capacitor required if the source is a half-wave rectifier output with a 60 Hz input.

Ans: 3800 μF

D1.12 If no resistor, R_F, were used in the circuit of Figure 1.31 and the transformer were a 4:1 center-tapped transformer with a 120 V rms 60 Hz input, what value of R_i would be needed to maintain 10 V across a load whose current varies from 50 mA to 200 mA? Assume that the minimum voltage allowed at the regulator input is 14 V.

Ans: 14.8 Ω

D1.13 What value of capacitor is needed in the regulator of Problem D1.12 in order to maintain a minimum voltage of 14 V?

Ans: 697 μF

D1.14 In the circuit of Problem D1.12, assume that the input voltage varies from 110 V to 120 V rms at 60 Hz. Select a value of capacitance that will