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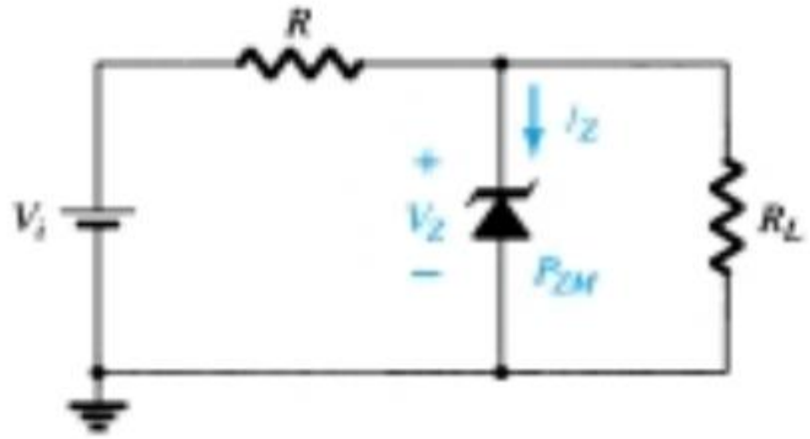
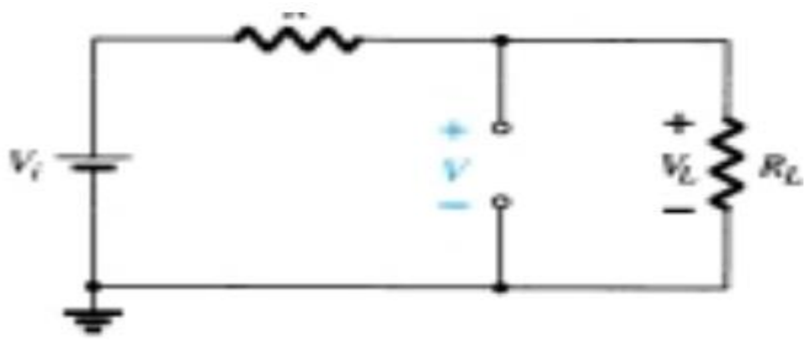
Lecture: ZENER DIODES

The analysis of networks employing Zener diodes is quite similar to that applied to the analysis of semiconductor diodes in previous sections. First the state of the diode must be determined followed by a substitution of the appropriate model and a determination of the other unknown quantities of the network. Unless otherwise specified, the Zener model to be employed for the "on" state will be as shown in Fig. 2.105a. For the "off" state as defined by a voltage less than V_Z but greater than 0 V with the polarity indicated in Fig. 2.105b, the Zener equivalent is the open circuit that appears in the same figure.





V_i and R

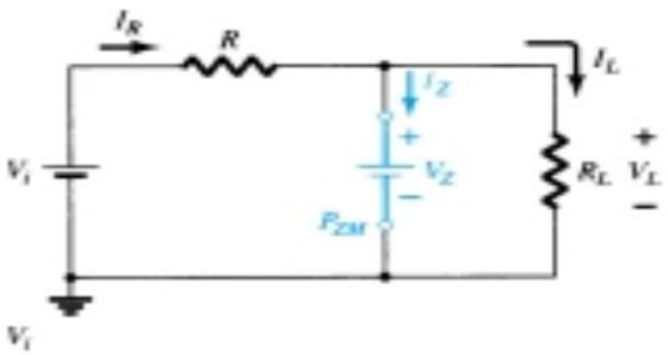
The simplest of Zener diode networks appears in Fig. 2.106. The applied dc voltage is fixed, as is the load resistor. The analysis can fundamentally be broken down into two steps.

1. *Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit.*

Applying step 1 to the network of Fig. 2.106 will result in the network of Fig. 2.107, where an application of the voltage divider rule will result in

$$V = V_L = \frac{R_L V_i}{R + R_L} \tag{2.16}$$

If $V \geq V_Z$, the Zener diode is "on" and the equivalent model of Fig. 2.105a can be substituted. If $V < V_Z$, the diode is "off" and the open-circuit equivalence of Fig. 2.105b is substituted.



2. ***Substitute the appropriate equivalent circuit and solve for the desired unknowns.***

For the network of Fig. 2.106, the "on" state will result in the equivalent network of Fig. 2.108. Since voltages across parallel elements must be the same, we find that

$$V_L = V_Z \tag{2.17}$$

The Zener diode current must be determined by an application of Kirchhoff's current law. That is,

$$I_R = I_Z + I_L$$

and

$$I_Z = I_R - I_L \tag{2.18}$$

where

$$I_L = \frac{V_L}{R_L} \quad \textit{and} \quad I_R = \frac{V_R}{R} = \frac{V_i - V_L}{R}$$

The power dissipated by the Zener diode is determined by

$$P_Z = V_Z I_Z \tag{2.19}$$

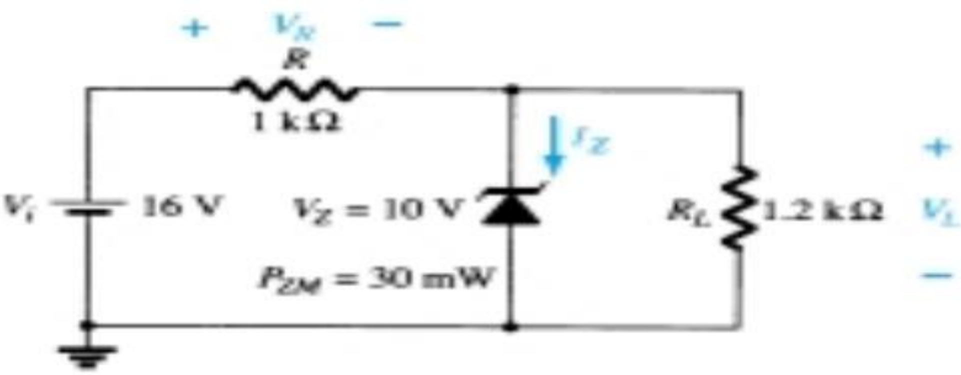
which must be less than the P_{ZM} specified for the device.

Before continuing, it is particularly important to realize that the first step was employed only to determine the *state of the Zener diode*. If the Zener diode is in the "on" state, the voltage across the diode is not V volts. When the system is turned on, the Zener diode will turn "on" as soon as the voltage across the Zener diode is V_Z volts. It will then "lock in" at this level and never reach the higher level of V volts.

Zener diodes are most frequently used in *regulator* networks or as a *reference* voltage. Figure 2.106 is a simple regulator designed to maintain a fixed voltage across the load R_L. For values of applied voltage greater than required to turn the Zener diode "on," the voltage across the load will be maintained at V_Z volts. If the Zener diode is employed as a reference voltage, it will provide a level for comparison against other voltages.

Example

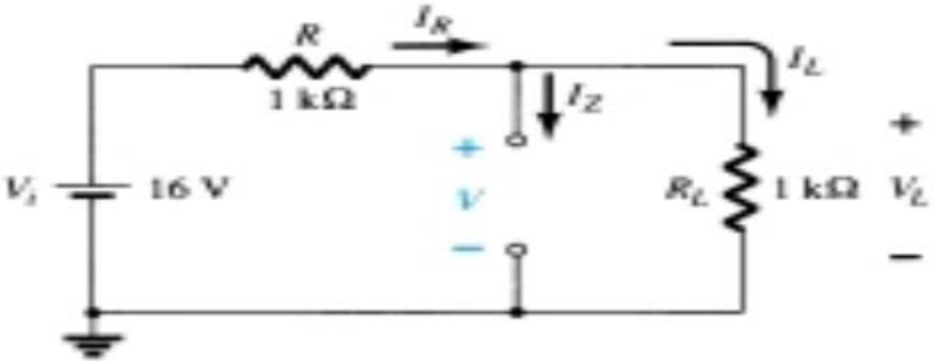
(a) For the Zener diode network of Fig. 2.109, determine V_L, V_R, I_Z, and P_Z.
(b) Repeat part (a) with $R_L = 3\ \text{k}\Omega$.



Solution

(a) Following the suggested procedure the network is redrawn as shown in Fig. 2.110. Applying Eq. (2.16) gives

$$V = \frac{R_L V_i}{R + R_L} = \frac{1.2\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 1.2\ \text{k}\Omega} = 8.73\ \text{V}$$



Since $V = 8.73$ V is less than $V_Z = 10$ V, the diode is in the "off" state as shown on the characteristics of Fig. 2.111. Substituting the open-circuit equivalent will result in the same network as in Fig. 2.110, where we find that

$$V_L = V = \mathbf{8.73\ V}$$

$$V_R = V_i - V_L = 16\ V - 8.73\ \text{V} = \mathbf{7.27\ V}$$

$$I_Z = \mathbf{0\ A}$$

and $$P_Z = V_Z I_Z = V_Z(0\ \text{A}) = \mathbf{0\ W}$$

(b) Applying Eq. (2.16) will now result in

$$V = \frac{R_L V_i}{R + R_L} = \frac{3\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 3\ \text{k}\Omega} = 12\ \text{V}$$

Since $V = 12$ V is greater than $V_Z = 10$ V, the diode is in the "on" state and the network of Fig. 2.112 will result. Applying Eq. (2.17) yields

$$V_L = V_Z = \mathbf{10\ V}$$

and $$V_R = V_i - V_L = 16\ \text{V} - 10\ \text{V} = \mathbf{6\ V}$$

with $$I_L = \frac{V_L}{R_L} = \frac{10\ \text{V}}{3\ \text{k}\Omega} = 3.33\ \text{mA}$$

and $$\text{I}_R = \frac{V_R}{R} = \frac{6\ \text{V}}{1\ \text{k}\Omega} = 6\ \text{mA}$$

so that $$I_Z = I_R - I_L\ [\text{Eq. (2.18)}]$$

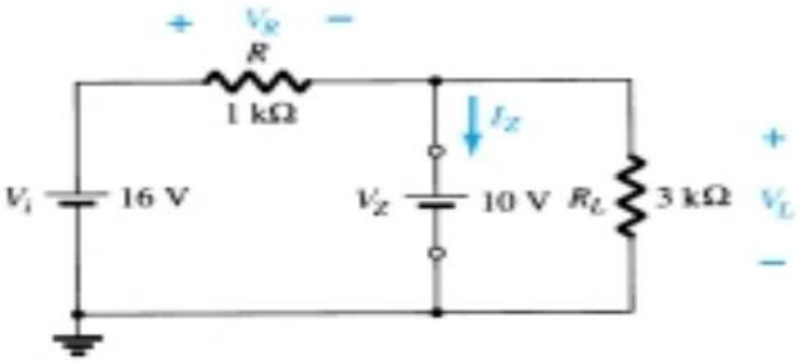
$$= 6\ \text{mA} - 3.33\ \text{mA}$$

$$= \mathbf{2.67\ mA}$$

The power dissipated,

$$P_Z = V_Z I_Z = (10\text{ V})(2.67\text{ mA}) = \mathbf{26.7\ mW}$$

which is less than the specified $P_{ZM} = 30$ mW.



Fixed V_i, Variable R_L

Due to the offset voltage V_Z, there is a specific range of resistor values (and therefore load current) which will ensure that the Zener is in the "on" state. Too small a load resistance R_L will result in a voltage V_L across the load resistor less than V_Z, and the Zener device will be in the "off" state.

To determine the minimum load resistance of Fig. 2.106 that will turn the Zener diode on, simply calculate the value of R_L that will result in a load voltage $V_L = V_Z$. That is,

$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

Solving for R_L, we have

$$R_{L_{\min}} = \frac{R V_Z}{V_i - V_Z} \tag{2.20}$$

Any load resistance value greater than the R_L obtained from Eq. (2.20) will ensure that the Zener diode is in the "on" state and the diode can be replaced by its V_Z source equivalent.

The condition defined by Eq. (2.20) establishes the minimum R_L but in turn specifies the maximum I_L as

$$I_{L_{\max}} = \frac{V_L}{R_L} = \frac{V_Z}{R_{L_{\min}}} \tag{2.21}$$

Once the diode is in the "on" state, the voltage across R remains fixed at

$$V_R = V_i - V_Z \tag{2.22}$$

and I_R remains fixed at

$$I_R = \frac{V_R}{R} \tag{2.23}$$

The Zener current

$$I_Z = I_R - I_L \tag{2.24}$$

resulting in a minimum I_Z when I_L is a maximum and a maximum I_Z when I_L is a minimum value since I_R is constant.

Since I_Z is limited to I_{ZM} as provided on the data sheet, it does affect the range of R_L and therefore I_L. Substituting I_{ZM} for I_Z establishes the minimum I_L as

$$I_{L_{\min}} = I_R - I_{ZM} \tag{2.25}$$

and the maximum load resistance as

$$R_{L_{\max}} = \frac{V_Z}{I_{L_{\min}}} \tag{2.26}$$

(a) For the network of Fig. 2.113, determine the range of R_L and I_L that will result in V_{R_L} being maintained at 10 V.
(b) Determine the maximum wattage rating of the diode.

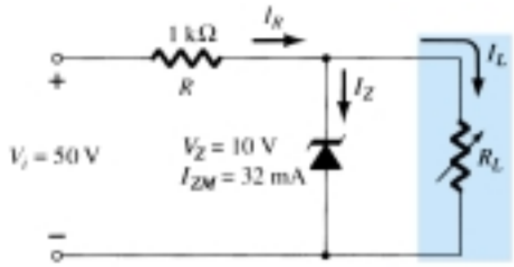


Figure 2.113 Voltage regulator for Example 2.27.

Solution

(a) To determine the value of R_L that will turn the Zener diode on, apply Eq. (2.20):

$$R_{L_{\min}} = \frac{RV_Z}{V_i - V_Z} = \frac{(1\text{ k}\Omega)(10\text{ V})}{50\text{ V} - 10\text{ V}} = \frac{10\text{ k}\Omega}{40} = \mathbf{250\ \Omega}$$

The voltage across the resistor R is then determined by Eq. (2.22):

$$V_R = V_i - V_Z = 50\text{ V} - 10\text{ V} = \mathbf{40\ V}$$

and Eq. (2.23) provides the magnitude of I_R:

$$I_R = \frac{V_R}{R} = \frac{40\text{ V}}{1\text{ k}\Omega} = \mathbf{40\ mA}$$

The minimum level of I_L is then determined by Eq. (2.25):

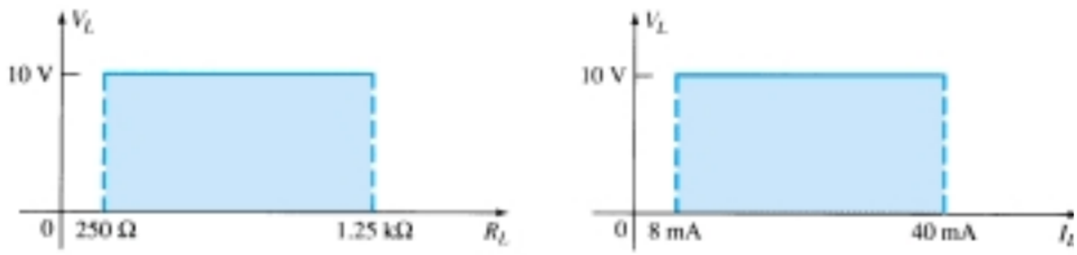
$$I_{L_{\min}} = I_R - I_{ZM} = 40\text{ mA} - 32\text{ mA} = \mathbf{8\ mA}$$

with Eq. (2.26) determining the maximum value of R_L:

$$R_{L_{\max}} = \frac{V_Z}{I_{L_{\min}}} = \frac{10\text{ V}}{8\text{ mA}} = \mathbf{1.25\ k\Omega}$$

A plot of V_L versus R_L appears in Fig. 2.114a and for V_L versus I_L in Fig. 2.114b.

(b) $P_{\max} = V_Z I_{ZM}$
$= (10\text{ V})(32\text{ mA}) = \mathbf{320\ mW}$



Fixed R_L, Variable V_i

For fixed values of R_L in Fig. 2.106, the voltage V_i must be sufficiently large to turn the Zener diode on. The minimum turn-on voltage $V_i = V_{i_{min}}$ is determined by

$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

and

$$V_{i_{min}} = \frac{(R_L + R)V_Z}{R_L} \tag{2.27}$$

The maximum value of V_i is limited by the maximum Zener current I_{ZM}. Since $I_{ZM} = I_R - I_L$,

$$I_{R_{max}} = I_{ZM} + I_L \tag{2.28}$$

Since I_L is fixed at V_Z/R_L and I_{ZM} is the maximum value of I_Z, the maximum V_i is defined by

$$V_{i_{max}} = V_{R_{max}} + V_Z$$

$$V_{i_{max}} = I_{R_{max}}R + V_Z \tag{2.29}$$

Determine the range of values of V_i that will maintain the Zener diode of Fig. 2.115 in the "on" state.

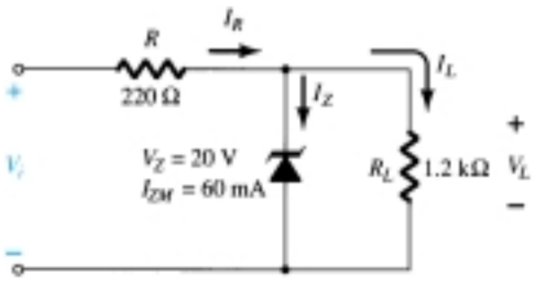


Figure 2.115 Regulator for Example 2.28.

Solution

$$\text{Eq. (2.27):}\quad V_{i_{min}} = \frac{(R_L + R)V_Z}{R_L} = \frac{(1200\ \Omega + 220\ \Omega)(20\ \text{V})}{1200\ \Omega} = \mathbf{23.67\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{20\ \text{V}}{1.2\ \text{k}\Omega} = 16.67\ \text{mA}$$

$$\text{Eq. (2.28):}\quad I_{R_{max}} = I_{ZM} + I_L = 60\ \text{mA} + 16.67\ \text{mA}$$
$$= 76.67\ \text{mA}$$

$$\text{Eq. (2.29):}\quad V_{i_{max}} = I_{R_{max}}R + V_Z$$
$$= (76.67\ \text{mA})(0.22\ \text{k}\Omega) + 20\ \text{V}$$
$$= 16.87\ \text{V} + 20\ \text{V}$$
$$= \mathbf{36.87\ V}$$

A plot of V_L versus V_i is provided in Fig. 2.116.

Zener Diode Applications:

1. AC Voltage Regulators (Limiters or Clippers):

Two back-to-back zeners can be used as an ac regulator or a simple square-wave generator as shown in Examples 7-1 and 7-2 respectively.

Example 7-1:

Sinusoidal ac regulator, see Fig. 7-3.

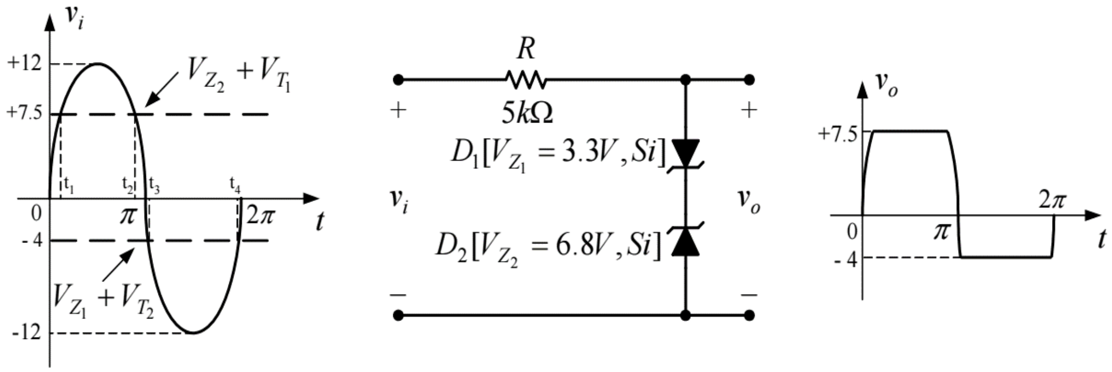


Fig. 7-3

For $t = 0 \rightarrow t_1$ and $t_2 \rightarrow \pi$; D_1 ON and D_2 OFF => $v_o = v_i$.

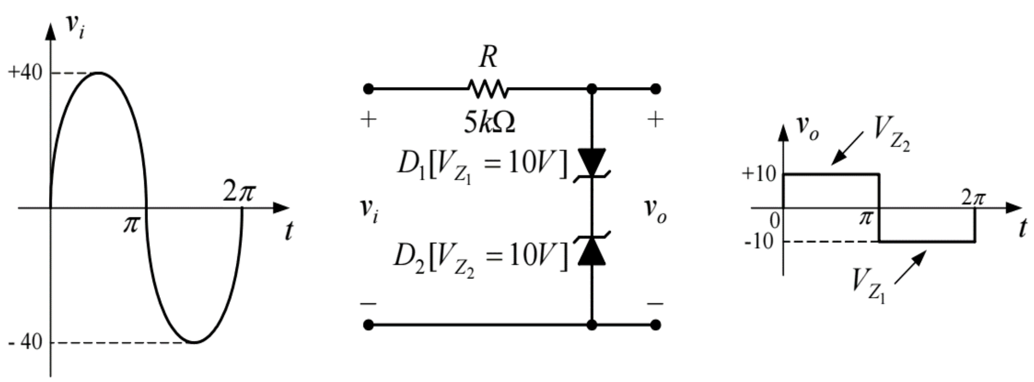
For $t = t_1 \rightarrow t_2$; D_1 ON and D_2 BREAKDOWN => $v_o = V_{Z_2} + V_{T_1}$.

For $t = \pi \rightarrow t_3$ and $t_4 \rightarrow 2\pi$; D_2 ON and D_1 OFF => $v_o = v_i$.

For $t = t_3 \rightarrow t_4$; D_2 ON and D_1 BREAKDOWN => $v_o = V_{Z_1} + V_{T_2}$.

Example 7-2:

Simple square-wave generator, see Fig. 7-4.



Example 7-3:

The reverse current in a certain 12 V, 2.4 W zener diode must be at least 5 mA to ensure that the diode remains in breakdown. The diode is to be used in the regulator circuit shown in Fig. 7-9, where V_i can vary from 18 V to 24 V. Find a suitable value for R_S and the minimum rated power dissipation that R_S should have.

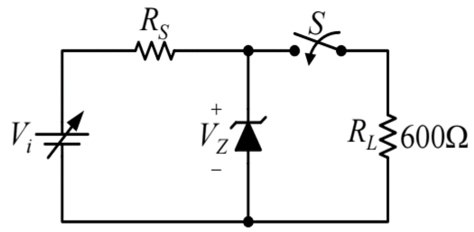


Fig. 7-9

Solution:

$I_{ZK} = 5mA$ and $I_{ZM} = \frac{P_Z}{V_Z} = \frac{2.4}{12} = 200mA$.

$I_{L(\min)} = 0A$ (when the switch S is open, $R_L = R_{L(\max)} = \infty\Omega$).

$I_{L(\max)} = \frac{V_Z}{R_{L(\min)}} = \frac{12}{600} = 20mA$ (when the switch S is closed, $R_L = R_{L(\min)} = 600\Omega$).

$I_{ZK} = I_{S(\min)} - I_{L(\max)}$ => $5*10^{-3} = I_{S(\min)} - 20*10^{-3}$ => $I_{S(\min)} = 25mA$.

$I_{ZM} = I_{S(\max)} - I_{L(\min)}$ => $200*10^{-3} = I_{S(\max)} - 0$ => $I_{S(\max)} = 200mA$.

$$R_{S(\max)} = \frac{V_{i(\min)} - V_Z}{I_{S(\min)}} = \frac{18-12}{25*10^{-3}} = 240\Omega.$$

$$R_{S(\min)} = \frac{V_{i(\max)} - V_Z}{I_{S(\max)}} = \frac{24-12}{200*10^{-3}} = 60\Omega.$$

Thus, we require $60\Omega \le R_S \le 240\Omega$.

Choosing or calculating $R_S = \sqrt{R_{S(\min)} \cdot R_{S(\max)}} = \sqrt{60*240} = 120\Omega$.

$$I_{S(\max)} = \frac{V_{i(\max)} - V_Z}{R_S} = \frac{24-12}{120} = 100mA.$$

$$P_{R_S} \ge I_{S(\max)}^2 \cdot R_S = \left(100*10^{-3}\right)^2 * 120 = 1.2W.$$

Exercises:

1. Sketch the output (v_o) for the circuit of Fig. 7-10 for the input shown (v_i) when $|V_m|$ equal to (i) 5 V, and (ii) 15 V.

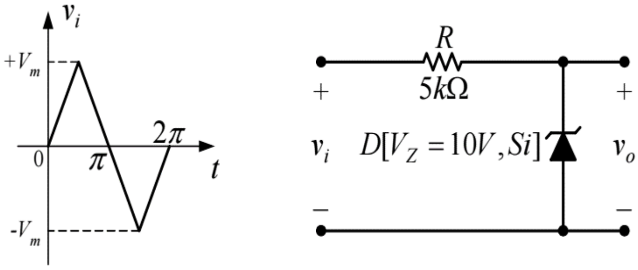


Fig. 7-10

2. Design the voltage regulator circuit of Fig. 7-11 to maintain V_L at 12 V across R_L with V_i that will vary between 16 and 20 V. That is, determine the proper value of R_S and the power rating of the zener diode (P_Z).

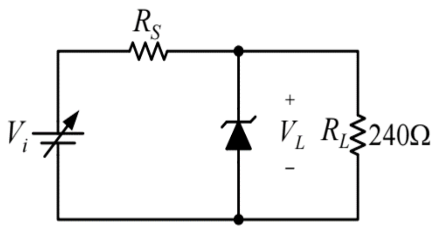


Fig. 7-11

3. The 6-V zener diode in Fig. 7-12 has a maximum rated power dissipated of 690 mW. Its reverse current must be at least 3 mA to keep it in breakdown. Find a suitable value for R_S if V_i can vary from 9 V to 12 V and R_L can vary from 500 Ω to 1.2 kΩ.

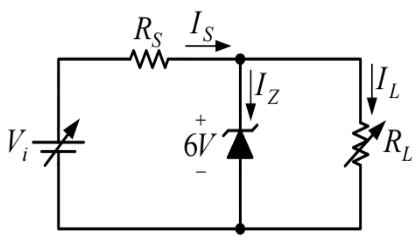


Fig. 7-12

4. If R_S in Exercise 3 is set equal to its maximum permissible value, what is the maximum permissible value of V_i?

5. If R_S in Exercise 3 is set equal to its minimum permissible value, what is the minimum permissible value of R_L?

6. If R_S in Exercise 3 is set equal to 120 Ω, what is the minimum rated power dissipated that R_S should have?