ENEE236

Analog Electronics

L6 Diode Applications 4
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Zener Diode
Simple Voltage Regulator

- *The Zener is used as a voltage regulator to maintain a constant dc output under variations in load current and ac line voltage*
- *It can also be used as protection device against overvoltage*
- *Analysis starts by defining state of diode followed by using appropriate model, then find unknown quantities*

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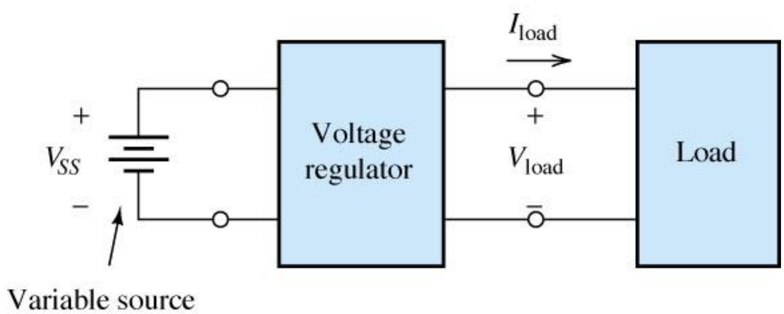
Voltage Regulator



A voltage regulator supplies constant voltage to a load.

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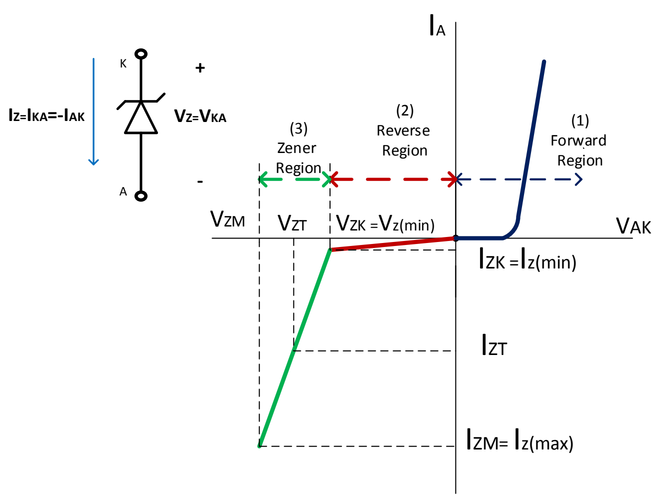
Zener Diode V-I Curve



- In data sheet , we have I_{ZT}, V_{ZT}
- Zener currents will be assumed positive if passing from cathode to Anode
- If I_Z< I_{ZK} zener will act as an open circuit
- If I_Z> I_{Zmax} zener will damaged
- If I_{ZK} < I_Z< I_{Zmax} zener will be in voltage regulation (zener) region

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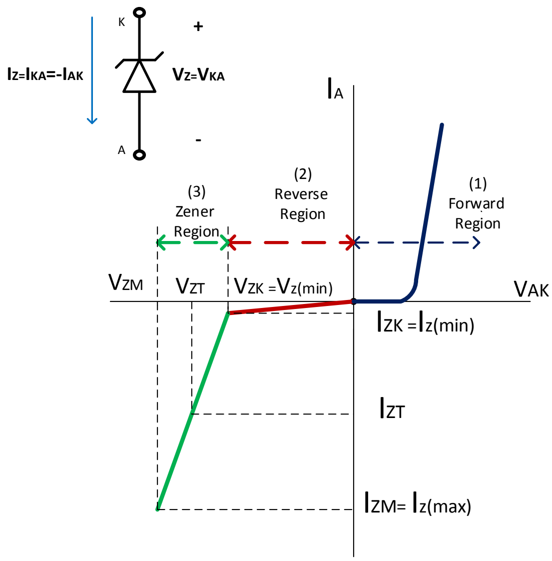
Zener Diode Operation Regions



Region (1)

- When VAK>0 , zener acts as regular diode ON
- Region (2)

When VZK<VAK<0 , zener acts as regular diode OFF

- Region (3)

When VZK>VAK ,
This is the intended operating region ,and the zener acts as a voltage regulator

- And VZ=VKA ,it can be replaced by either a battery or a battery in series with resistor rZ

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Zener Diode Operation & Models

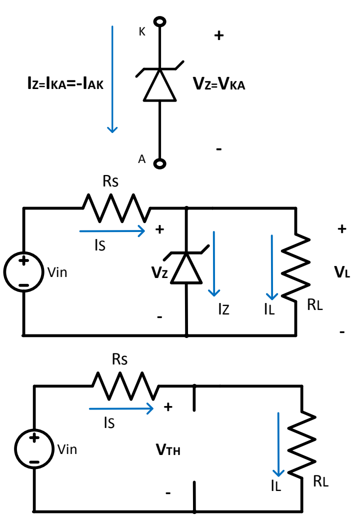
The Zener is a diode that is operated in reverse bias at the Zener Voltage (V_z).

Conditions for zener diode to operate in the breakdown (Zener/ON) region When

1. **Cathode is more positive than anode**
2. **$V_{th} \geq V_Z$**
3. **Iz > Iz(min)**
4. **Iz< Iz(max)**

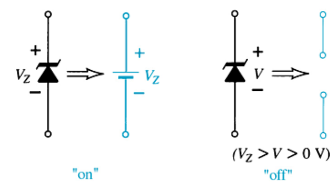
==> Voltage across the Zener is V_Z

- Zener current: $I_Z = I_S - I_L$
- The Zener Power: $P_Z = V_Z I_Z$

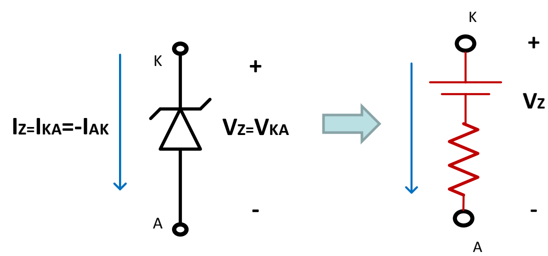


Zener Diode Models

1. Ideal Model



2. Simplified Model



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Fixed Vin, Variable RL

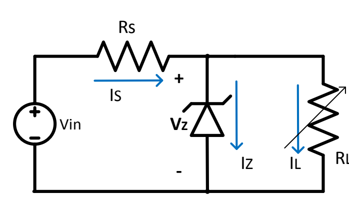
- *Due to the value of Vz, there is specific values of RL (IL) that ensure the zener is in the ON (regulation) state*
- *Too small values of RL can result in zener being OFF*

$$V_L = V_Z = \frac{R_L}{R_L + R_S} V_{in}$$

$$R_{L(\min)} = \frac{R_S . V_Z}{V_{in} - V_Z}$$

$$R_L \geq R_{L(\min)} \Rightarrow I_{L(\max)} = \frac{V_L}{R_L} = \frac{V_L}{R_{L(\min)}}$$

Also, values of $R_L \geq R_{L(\max)}$ can result in $\Rightarrow I_Z > I_{Z(\max)}$



$$I_{L(\min)} = I_S - I_{Z(\max)}$$
$$\Downarrow$$
$$R_{L(\max)} = \frac{V_Z}{I_{L(\min)}}$$

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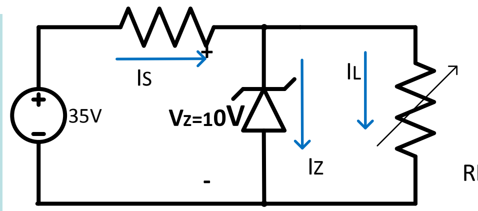
Example

Given the following values of R_L, find the mode of operation of the zener and the voltage V_L, assume $Rs = 1\,k\Omega$

a) $R_L = 0.1\,k\Omega$
b) $R_L = 0.5\,k\Omega$
c) $R_L = 5\,k\Omega$
d) $R_L = \infty$



SOLUTION

a) $R_L = 0.1\,k\Omega$

using ideal model

$$V_{th} = \frac{R_L}{R_L + R_S} V_{in} = \frac{0.1}{0.1+1} 35\,V = 3.18\,V$$

Zener works in region 2, it acts as open circuit

$V_L = 3.18\,V$ (it is not regulated)

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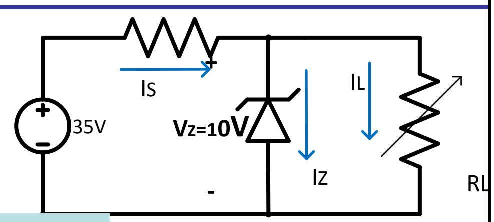
Example



b) $R_L = 0.5\,k\Omega$

using ideal model

$$V_{th} = \frac{R_L}{R_L + R_S} V_{in} = \frac{0.5}{0.5+1} 35\,V = 11.67\,V$$

$V_{th} > V_Z$

Zener works in region 3, it works as voltage regulator

$V_L = V_Z = 10\,V$

$$I_S = \frac{35\,V - 10\,V}{1\,k\Omega} = 25\,mA$$

$$I_L = \frac{V_L}{R_L} = \frac{10}{0.5k\Omega} = 20\,mA$$

$I_Z = I_S - I_L = 5\,mA$

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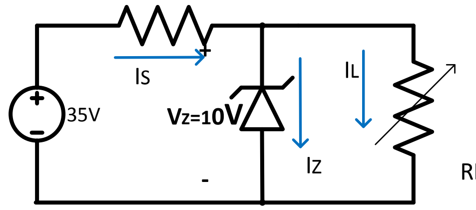
Example



c) $R_L = 5\,k\Omega$

using ideal model

$$V_{th} = \frac{R_L}{R_L + R_S} V_{in} = \frac{5}{5+1} 35\ V = 29.17\ V$$

$$V_{th} > V_Z$$

Zener works in region 3, it works as voltage regulator

$$V_L = V_Z = 10\ V$$

$$I_S = \frac{35\ V - 10\ V}{1\,k\Omega} = 25\ mA$$

$$I_L = \frac{V_L}{R_L} = \frac{10}{5k\Omega} = 2\ mA$$

$$I_Z = I_S - I_L = 23\ mA$$

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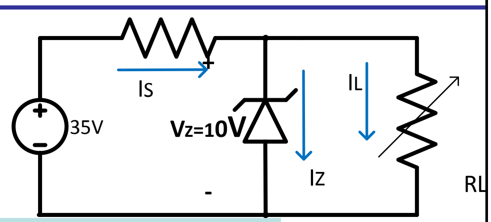
Example



d) $R_L = \infty$

using ideal model

$$V_{th} = \frac{\infty}{\infty + R_S} V_{in} = 35\ V$$

$$V_{th} > V_Z$$

Zener works in region 3, it works as voltage regulator

$$V_L = V_Z = 10\ V$$

$$I_S = \frac{35\ V - 10\ V}{1\,k\Omega} = 25\ mA$$

$$I_L = \frac{V_L}{} = \frac{10}{} = 0$$

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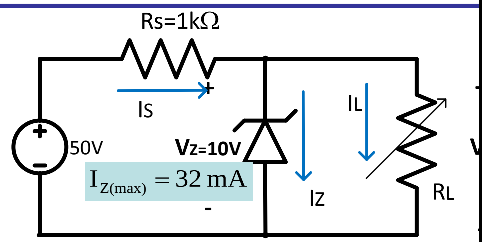
Example

1) Determine Range of R_L & I_L that will result in V_L be maintained at 10V
2) Determine the power rating of the zener diode



SOLUTION

1) To find $R_{L(min)}$ that will turn the zener diode ON:

$$V_L = V_Z = \frac{R_L}{R_L + R_S} V_i \Rightarrow$$

$$R_L = \frac{R_S}{V_i - V_Z} V_Z$$

$$R_{L(min)} = \frac{1\,k\Omega}{50-10} 10 = 250\,\Omega$$

2) To find $R_{L(max)} \Rightarrow$ we need $I_{L(min)}$

$$I_{L(min)} = I_S - I_{Z(max)}$$

$$I_S = \frac{V_i - V_Z}{R_S} = \frac{50-10}{1\,k\Omega} = 40\text{ mA}$$

$$I_{L(min)} = 40 - 32 = 8\text{ mA}$$

$\Downarrow$

$$R_{L(max)} = \frac{V_L}{I_{L(min)}} = \frac{10\text{ V}}{8\text{ mA}} = 1.25\,k\Omega$$

$$250\,\Omega \le R_L \le 1.25\,k\Omega$$

3) $P_{Z(max)} = V_Z . I_{Z(max)} = 10\text{ V} \; . \; 32\text{ mA} = 320\text{ mW}$
The zener diode is chosen with power rating $\ge P_{Z(max)}$

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Fixed RL, Variable Vin

For Fixed RL, the voltage Vin must be large enough to turn the zener diode on (regulation region (3))

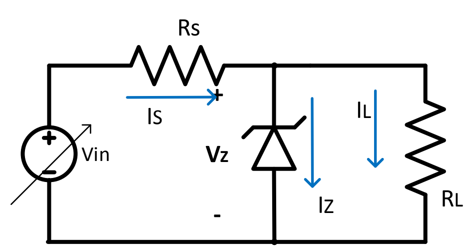
$$V_{in} = V_{in(min)} = \frac{R_L + R_S}{R_L} V_Z$$

$V_{in(max)}$ is limited by maximum zener current $I_{Z(max)}$

$$I_S = I_Z + I_L$$
$$I_{S(max)} = I_{z(max)} + I_L$$
$$V_{i(max)} = I_{S(max)} . R_S + V_Z$$

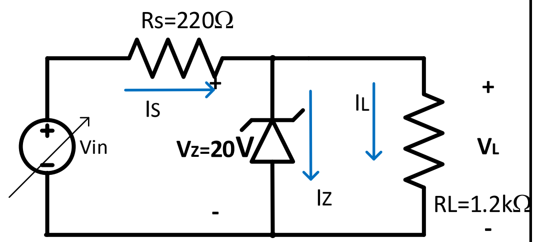
$\Downarrow$

$$V_{in(min)} \le V_{in} \le V_{in(max)}$$



Example

Find the range of values of Vi that will maintain the zener in the ON (regulation) State



$$V_{in(min)} = \frac{R_L + R_S}{R_L} V_Z$$

$$= \frac{1200 + 220}{1200} 20 = 23.07\ \text{V}$$

$$I_{Z(max)} = 60\ \text{mA}$$

$$I_S = I_Z + I_L$$

$$I_{S(max)} = I_{z(max)} + I_L$$

$$I_L = \frac{V_L}{R_L} = \frac{20\ \text{V}}{1200\ \Omega} = 16.67\ \text{mA}$$

$$I_{S(max)} = 60\ \text{mA} + 16.67\ \text{mA} = 76.67\ \text{mA}$$

$$V_{i(max)} = (76.67\ \text{mA}).(220\ \Omega) + 20\ \text{V} = 36.87\ \text{V}$$

$$\therefore\ 23.07\ \text{V} \le V_{in} \le 36.87\ \text{V}$$

Design of Rs (Current limiting Resistor)

Given : $V_Z, I_{Z(min)}, I_{Z(max)}, V_{in(min)}, V_{in(max)}, R_{L(min)}, R_{L(max)}$

Find range of acceptable Rs in the voltage regulator

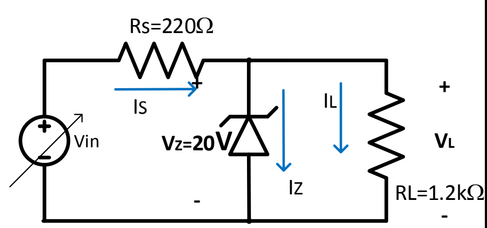
1) $I_Z = I_S - I_L \ge I_{Z(min)}$

Worst Case : the smallest value of

$(I_S - I_L)$

must be always higher than $> I_{Z(min)}$

$I_{S(min)} - I_{L(max)} \ge I_{Z(min)}$



$$\frac{V_{S(min)} - V_Z}{R_S} - I_{L(max)} \ge I_{Z(min)}$$

$$I_{Z(min)} + I_{L(max)} \le \frac{V_{S(min)} - V_Z}{R_S}$$

$$R_S \le \frac{V_{S(min)} - V_Z}{I_{Z(min)} + I_{L(max)}}$$

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Design of Rs (Current limiting Resistor)

Given : $V_Z, I_{Z(min)}, I_{Z(max)}, V_{in(min)}, V_{in(max)}, R_{L(min)}, R_{L(max)}$

Find range of acceptable Rs in the voltage regulator

2) $I_Z \le I_{Z(max)}$

Worst Case : the largest value of $(I_S - I_L)$ must be always smaller than $I_{Z(max)}$

$I_{S(max)} - I_{L(min)} \le I_{Z(max)}$

$$\frac{V_{S(max)} - V_Z}{R_S} - I_{L(min)} \le I_{Z(max)}$$

$$I_{Z(max)} + I_{L(min)} \ge \frac{V_{S(max)} - V_Z}{R_S}$$

$$R_S \ge \frac{V_{S(max)} - V_Z}{I_{Z(max)} + I_{L(min)}}$$

Note That

$$I_{L(min)} = \frac{V_Z}{R_{L(max)}}$$

$$I_{L(max)} = \frac{V_Z}{R_{L(min)}}$$

$$\frac{V_{S(min)} - V_Z}{I_{Z(min)} + I_{L(max)}} \ge R_S \ge \frac{V_{S(max)} - V_Z}{I_{Z(max)} + I_{L(min)}}$$

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Design of Rs (Current limiting Resistor)

Given :

$V_Z = 10\ \text{V}$,

$I_{Z(min)} = 5\ \text{mA}, I_{Z(max)} = 200\ \text{mA}$,

$V_{in(min)} = 15\ \text{V}, V_{in(max)} = 20\ \text{V}$,

$R_{L(min)} = 500, R_{L(max)} = \infty$

Find R_s?

$$\frac{V_{S(min)} - V_Z}{I_{Z(min)} + I_{L(max)}} \ge R_S \ge \frac{V_{S(max)} - V_Z}{I_{Z(max)} + I_{L(min)}}$$

Solution

$$I_{L(min)} = \frac{V_Z}{R_{L(max)}} = \frac{10\ \text{V}}{500\ \Omega} = 20\ \text{mA}$$

$$I_{L(max)} = \frac{V_Z}{R_{L(min)}} = \frac{10\ \text{V}}{\infty} = 0$$

$200\ \Omega \ge R_S \ge 50\ \Omega$

let $R_S = 100\ \Omega$

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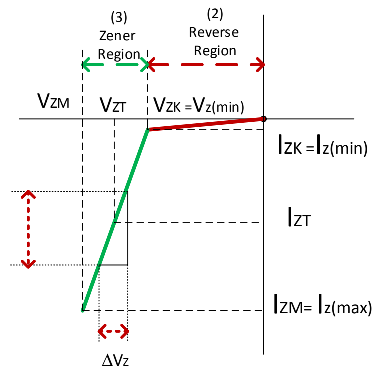
Variation of Vz (using simplified model)

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

If V_{ZT}, I_{ZT} & r_Z are known

$$V_{Z(max)} = V_{ZM} = V_{ZT} + \Delta I_Z \cdot r_Z$$
$$= V_{ZT} + (I_{Z(max)} - I_{ZT}) \cdot r_Z$$
$$V_{Z(min)} = V_{ZK} = V_{ZT} - \Delta I_Z \cdot r_Z$$
$$= V_{ZT} - (I_{ZT} - I_{Z(min)}) \cdot r_Z$$



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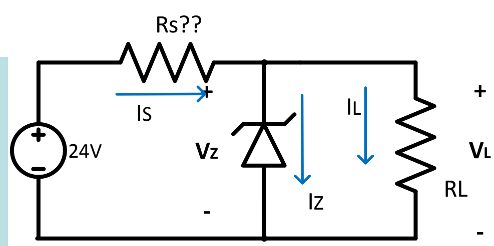
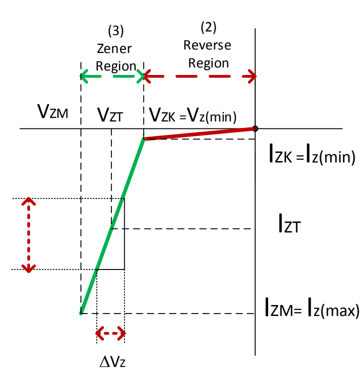
Example

If $V_{ZT} = 15V$ at $I_{ZT} = 17mA$
& $r_{ZT} = 14\,\Omega$
$I_{ZK} = 0.25\,mA$
$P_{Zmax} = 1\,Watt$
Find :
1) Minimum and Maximum Values of Vz
2) Value of R_S
3) Value of $R_{L(min)}$



$$1)\quad I_{Z(max)} \cong \frac{P_{Z(max)}}{V_Z} = \frac{1\,Watt}{15} = 66.7\ mA$$

$$V_{Z(max)} = V_{ZM} = V_{ZT} + \Delta I_Z \cdot r_Z$$
$$= V_{ZT} + (I_{Z(max)} - I_{ZT}) \cdot r_Z$$
$$= 15 + (66.7 - 17)\ mA\ (14\,\Omega) = 15.7\ V$$
$$V_{Z(min)} = V_{ZK} = V_{ZT} - \Delta I_Z \cdot r_Z$$
$$= V_{ZT} - (I_{ZT} - I_{Z(min)}) \cdot r_Z$$



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Example

$$V_{Z(min)} = V_{ZK} = V_{ZT} - \Delta I_Z \,.\, r_Z$$
$$= V_{ZT} - (I_{ZT} - I_{Z(min)})\,.\, r_Z$$
$$= 15 - (17 - 0.25)\ mA\ (14\,\Omega) = 14.76\ V$$

2) R_S

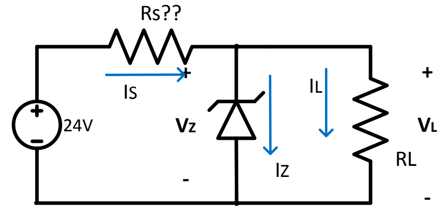
$$\frac{V_{S(min)} - V_Z}{I_{Z(min)} + I_{L(max)}} \geq R_S \geq \frac{V_{S(max)} - V_Z}{I_{Z(max)} + I_{L(min)}}$$

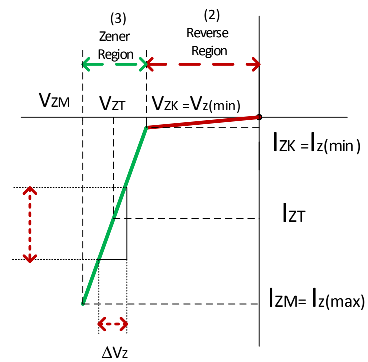
Here $V_{IN} = V_S$ is fixed $\Rightarrow$

$$R_S \geq \frac{V_S - V_{Z(max)}}{I_{Z(max)} + I_{L(min)}} = \frac{24 - 15.7}{66.7\ mA + 0} = 124\,\Omega$$

$$R_S \leq \frac{V_S - V_{Z(min)}}{I_{Z(min)} + I_{L(max)}} = \frac{24 - 14.76}{0.25\ mA + ???}$$

we choose $R_S = 124\Omega$





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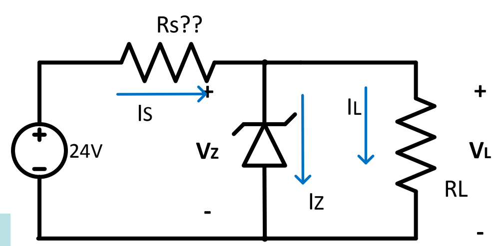
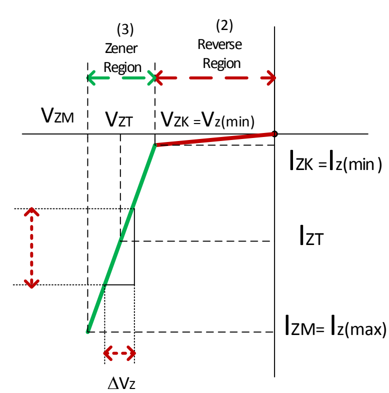
Example

3) $R_{L(min)} \Rightarrow I_{L(max)}$

$$I_{L(max)} = I_S - I_{L(min)}$$
$$= 66.7\ mA - 0.25\ mA = 66.45\ mA$$

$$\therefore\ R_{L(min)} = \frac{V_{Z(min)}}{I_{L(max)}} = \frac{14.76\ V}{66.45\ mA} \cong 222\,\Omega$$





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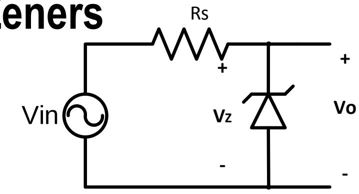
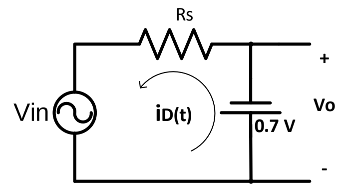
Clipper circuits using Zeners

a) When $V_i(t) < -0.7$ V, Zener works in region (1) as regular diode ON

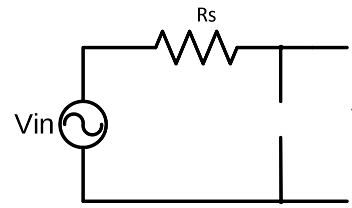
$$0.7 + i_D(t).R + V_i(t) = 0$$
$$i_D(t) = \frac{-V_i(t) - 0.7}{R} > 0$$
$$V_i(t) < -0.7$$
$$\therefore V_O(t) = -0.7$$





b) When $V_Z > V_i(t) > -0.7$ V, Zener works in region (2) as regular diode OFF

$$\therefore V_O(t) = V_i(t)$$



c) When $V_i(t) > V_Z$, Zener works in region (3) as voltage regulator

$$\therefore V_O(t) = V_Z$$

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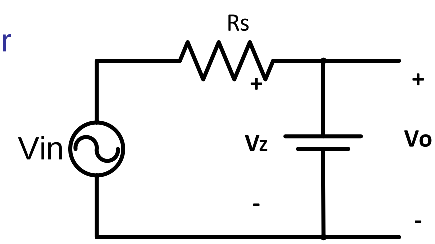
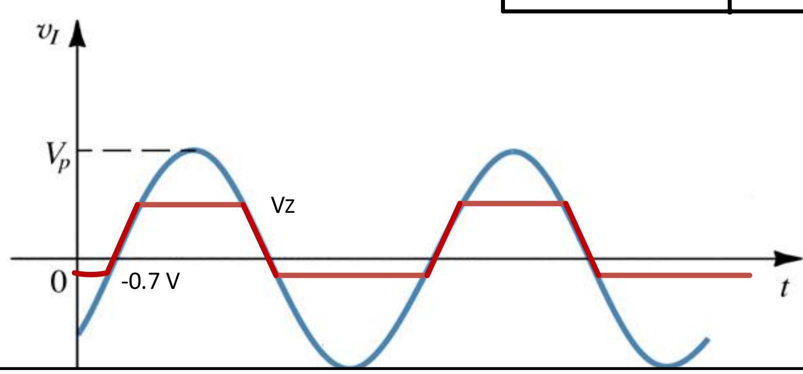
Clipper circuits using Zeners

c) When $V_i(t) > V_Z$, Zener works in region (3) as voltage regulator

$$\therefore V_O(t) = V_Z$$

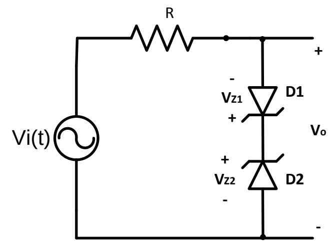




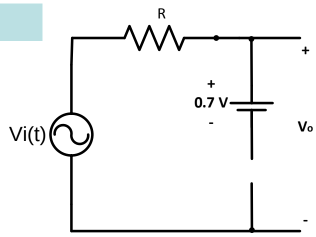
Clipper circuits using Zeners

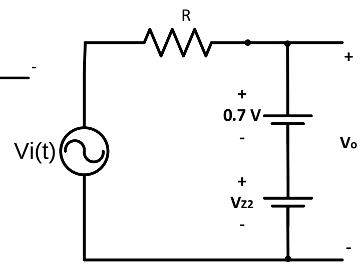
Find and sketch $V_o(t)$

a) When $0.7V < V_i(t) < V_{Z2}$,
D1- regular diode ON
D2- regular diode OFF



$\therefore V_O(t) = V_i(t)$





b) When $V_i(t) > V_{Z2}$
D1 – ON (region 1)
D2- Zener ON (region 3)

$\therefore V_O(t) = V_{Z2} + 0.7$

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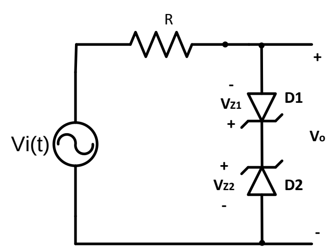
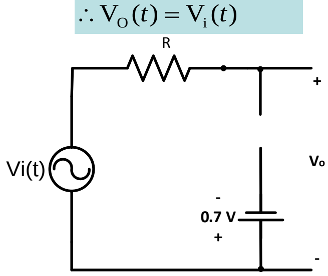
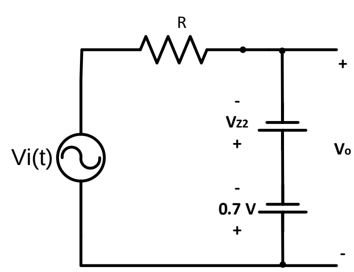
Clipper circuits using Zeners

c) When $-0.7V > V_i(t) > -V_{Z1}$,
D1- regular diode OFF
D2- regular diode ON



$\therefore V_O(t) = V_i(t)$





d) When $V_i(t) < -V_{Z1}$
D2 – ON (region 1)
D1- Zener ON (region 3)

$\therefore V_O(t) = -V_{Z1} - 0.7$

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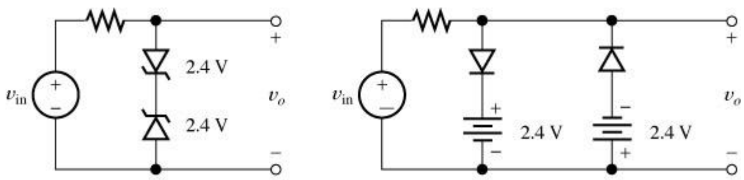
Clipper circuits using zeners



(c) Circuits for the characteristic of part (a)

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Voltage-Multiplier Circuits

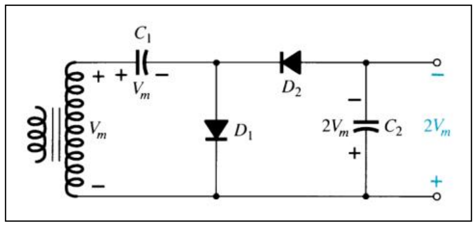
Voltage multiplier circuits use a combination of diodes and capacitors to step up the output voltage of rectifier circuits. Three common voltage multipliers are the:

Voltage Doubler

Voltage Tripler

Voltage Quadrupler

Voltage Doubler



This half-wave voltage doubler's output can be calculated using:

$$V_{out} = V_{C2} = 2V_m$$

where V_m = peak secondary voltage of the transformer

Voltage Doubler

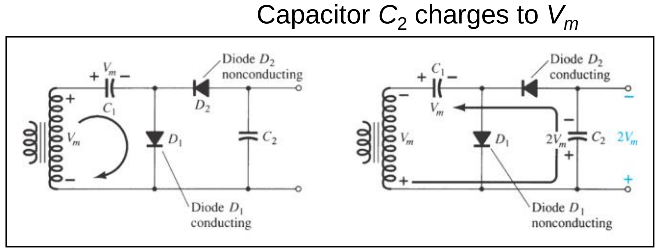
Positive Half-Cycle

D_1 conducts
D_2 is switched off
Capacitor C_1 charges to V_m

Negative Half-Cycle

D_1 is switched off
D_2 conducts
Capacitor C_2 charges to V_m

$V_{out} = V_{C2} = 2V_m$



Voltage Tripler and Quadrupler