ENEE2360

Analog Electronics

T5:
Zener Diode

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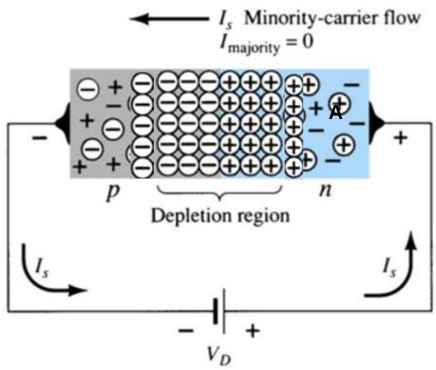
Zener Diode
Simple Voltage Regulator

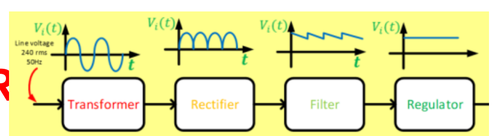
- *The Zener is used as a voltage regulator to maintain a constant dc output under variations in load current and ac line voltage*
- *It can also be used as protection device against overvoltage*
- *Analysis starts by defining state of diode followed by using appropriate model, then find unknown quantities*

Reverse bias of a pn junction Breakdown Voltage



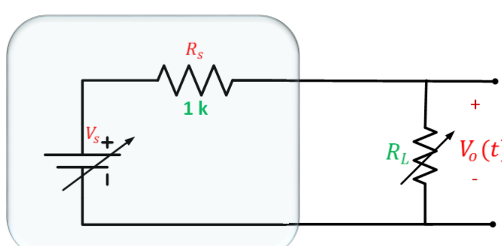
The electric field may become large enough for the covalent bond to break, causing electron-hole pairs to be created.

R

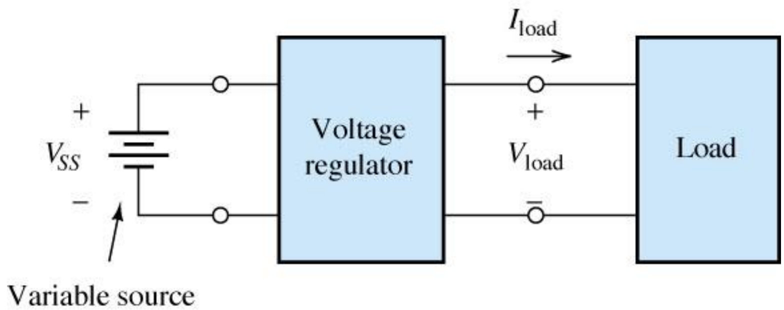


Used to maintain a constant dc output voltage under variation in the load current from the dc power supply and under variation in the ac line voltage

$V_o = \frac{RL}{RL+RS} \cdot Vs$

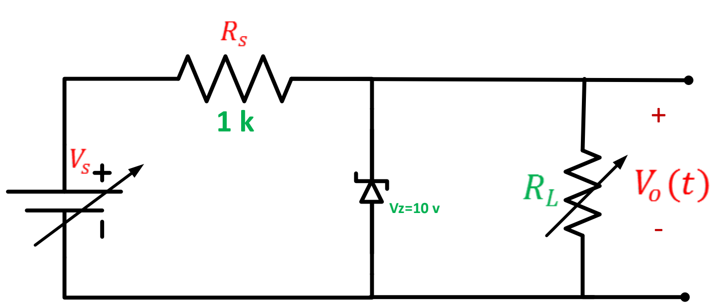


Voltage Regulator



A voltage regulator supplies constant voltage to a load.

Simple voltage regulator



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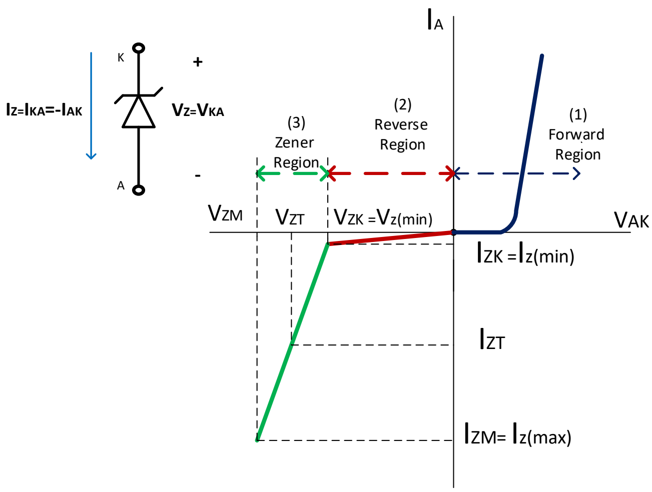
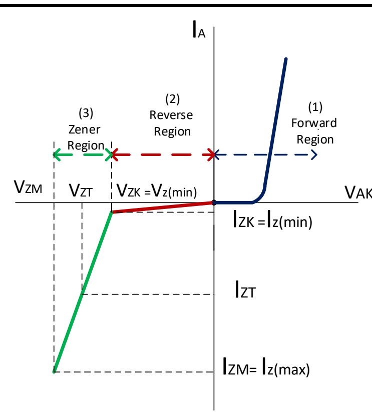
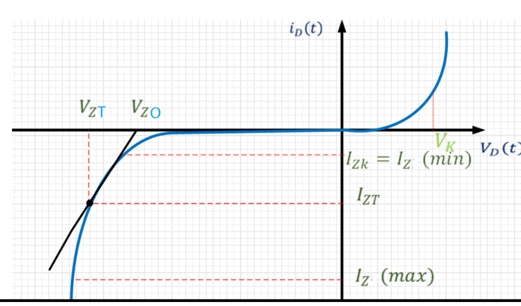
Zener Diode V-I Curve



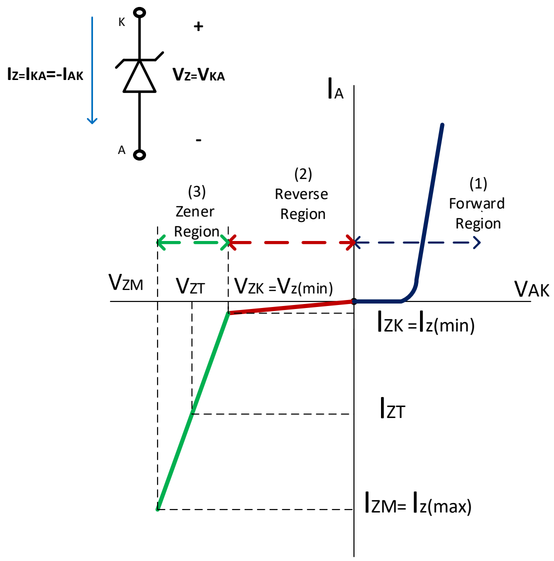
- In data sheet , we have I_{ZT}, V_{ZT}
- Zener currents will be assumed positive if passing from cathode to Anode
- If $I_Z < I_{ZK}$ zener will act as an open circuit
- If $I_Z > I_{Zmax}$ zener will damaged
- If $I_{ZK} < I_Z < I_{Zmax}$ zener will be in voltage regulation (zener) region



Also we must make sure that
I_Z(max) ≥ I_Z ≥ I_Z(min)
For the Zener diode to operate safely in the breakdown region .



Zener Diode Operation Regions



Region (1)
- When VAK>0 , zener acts as regular diode ON

- Region (2)
When 0 <VKA<VZK , zener acts as regular diode OFF

- Region (3)
When VKA>VZK ,
This is the intended operating region ,and the zener acts as a voltage regulator

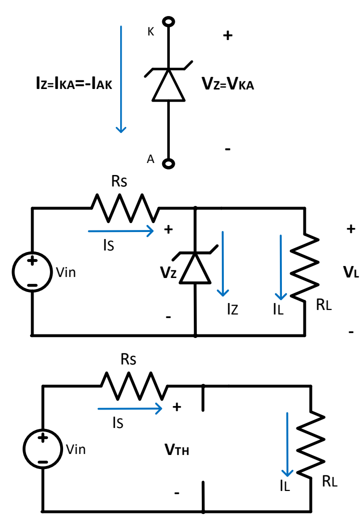
Zener Diode Operation & Models

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

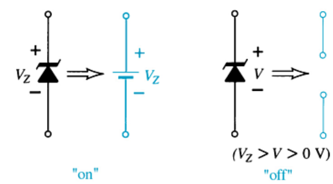
1. **Cathode is more positive than anode**
2. **$V_{th} \geq V_Z$**
3. **Iz > Iz(min)**
4. **Iz< Iz(max)**

==> Voltage across the Zener is V_Z
- Zener current: $I_Z = I_S - I_L$
- The Zener Power: $P_Z = V_Z I_Z$

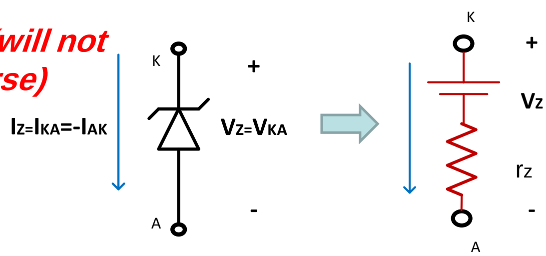


Zener Diode Models

1. Ideal Model

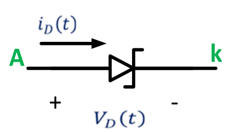


2. Simplified Model ***(will not be used in this course)***



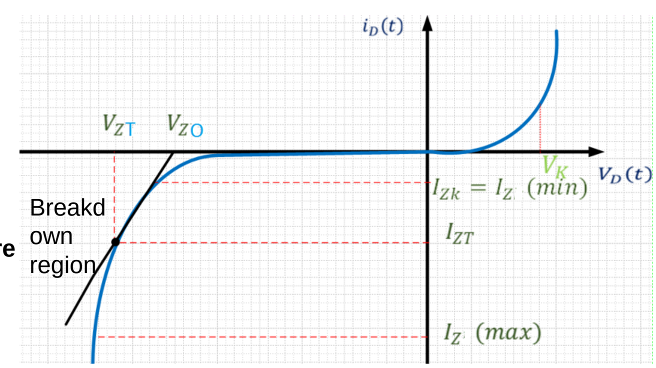
Zener Diode

V-I Characteristic curve



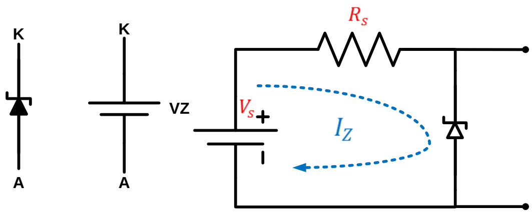
V_{ZT} = X @ I_{ZT} = Y

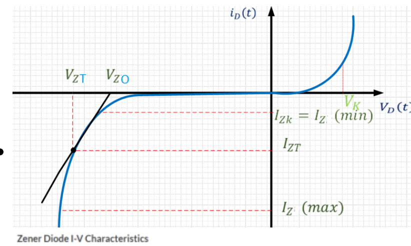
$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$



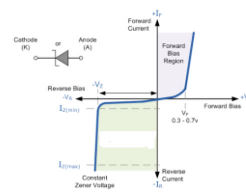
Also we must make sure that
I_Z(max) ≥ I_Z ≥ I_Z(min)
For the Zener diode to operate safely in the breakdown region .

Ideal model of Zener in the breakdown region .





- If $V_S > V_Z$, the Zener diode is in the breakdown region .
- If $V_S < V_Z$, the Zener diode is open circuit.



Also we must make sure that

- $I_Z(\max) \geq I_Z \geq I_Z(\min)$

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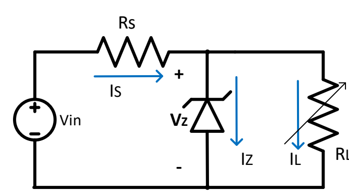
Fixed Vin, Variable RL

- *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*

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

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

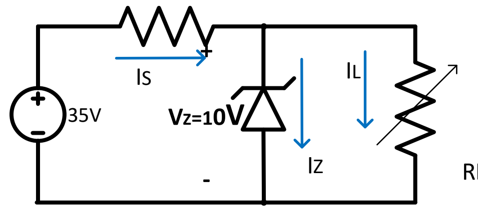
$$R_L \geq R_{L(\min)} \Rightarrow I_{L(\max)} = \frac{V_L}{R_L} = \frac{V_L}{R_{L(\min)}}$$



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

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

Example



Given the following values of R_L, find the mode of operation of the zener and the voltage V_L

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) $R_L = 0.1\,k\Omega$

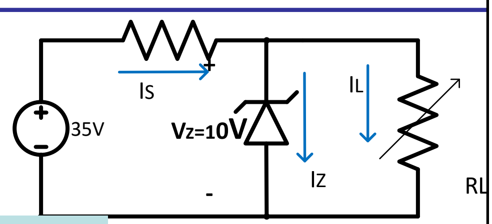
using ideal model

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

Zener works in region 2, it acts as open circuit

$V_L = 3.18\text{ V}$ (it is not regulated)

Example



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

using ideal model

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

$V_{th} > V_Z$

Zener works in region 3, it works as voltage regulator

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

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

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

$I_Z = I_S - I_L = 5\text{ mA}$

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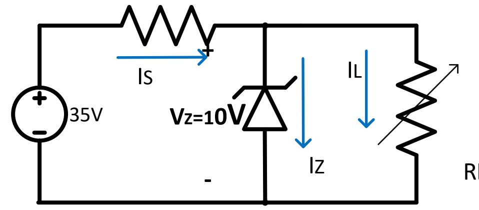
Example



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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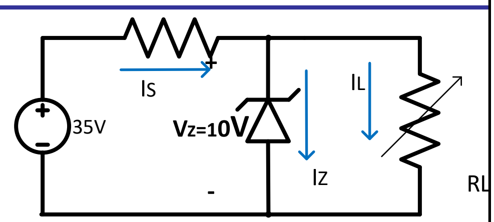
Example



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

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

$V_L = V_Z = 10\,V$

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

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

$I_Z = I_S - I_L = 25\,mA$

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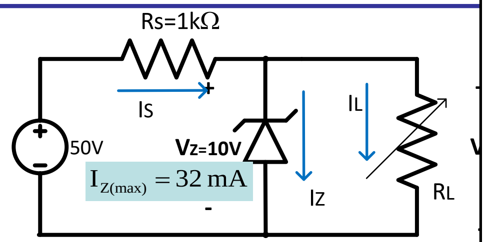
Example

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



$I_{Z(max)} = 32\text{ mA}$

SOLUTION

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

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

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

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

$$250\ \Omega \le R_L \le 1.25\text{ k}\Omega$$

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

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

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

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

$\Downarrow$

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

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 $I_{Z(max)}$

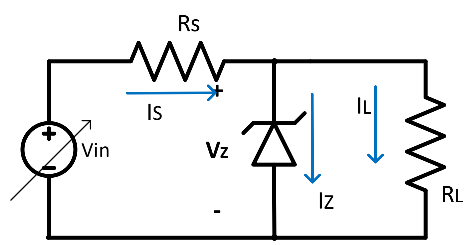
$$I_S = I_Z + I_L$$

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

$$V_{i(max)} = I_{S(max)} . R_S + V_Z$$

$\Downarrow$

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



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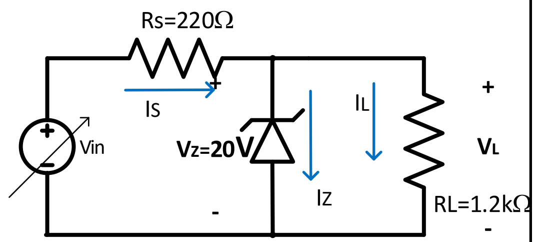
Example

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



$$V_{in(min)} = \frac{R_L + R_S}{R_L} V_Z$$
$$= \frac{1200 + 220}{1200} 20 = 23.07\ V$$

$$I_S = I_Z + I_L$$
$$I_{S(max)} = I_{z(max)} + I_L$$
$$I_L = \frac{V_L}{R_L} = \frac{20\ V}{1200\ \Omega} = 16.67\ mA$$

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

$$I_{S(max)} = 60\ mA + 16.67\ mA = 76.67\ mA$$
$$V_{i(max)} = (76.67\ mA).(220\ \Omega) + 20\ V = 36.87\ V$$

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

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Design of Rs (Current limiting Resistor)

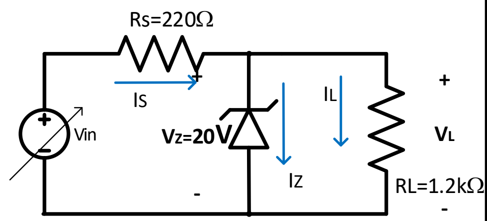
Given : $V_Z, I_{Z(min)}, I_{Z(max)}, V_{in(min)}, V_{in(max)}, R_{L(min)}, R_{L(max)}$

Find range of acceptable Rs in the voltage regulator

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 :

$V_Z = 10$ V,

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

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

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

Find R_s?

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

I_L**(max) =** $\frac{V_Z}{R_L\text{(min)}}$**=10/500=20mA**

and

I_L**(min) =** $\frac{V_Z}{R_L\text{(max)}}$**=10/infinity=0**

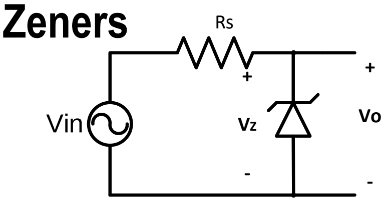
$200\,\Omega \ge R_S \ge 50\,\Omega$

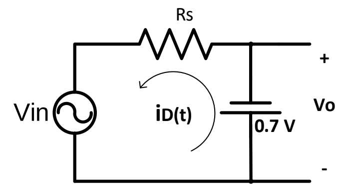
let $R_S = 100\,\Omega$

Clipper circuits using Zeners

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

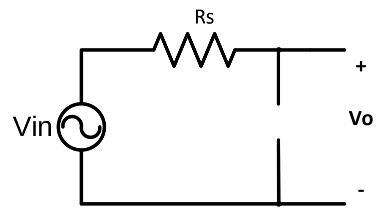
$$0.7 + i_D(t).R + V_i(t) = 0$$
$$i_D(t) = \frac{-V_i(t) - 0.7}{R} > 0$$
$$V_i(t) < -0.7$$
$$\therefore V_O(t) = -0.7$$





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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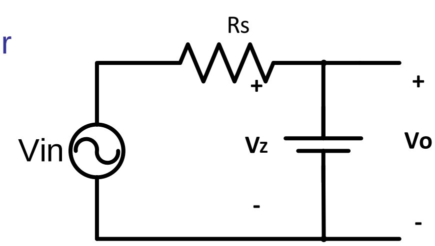
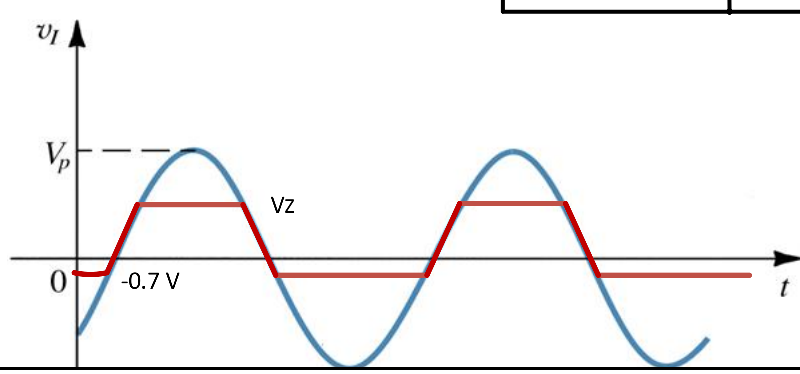
Clipper circuits using Zeners

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

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





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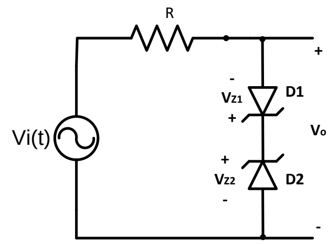
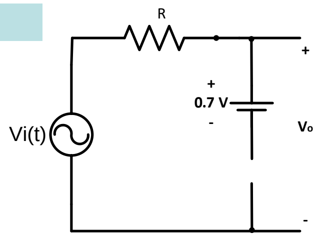
Clipper circuits using Zeners

Find and sketch $V_o(t)$

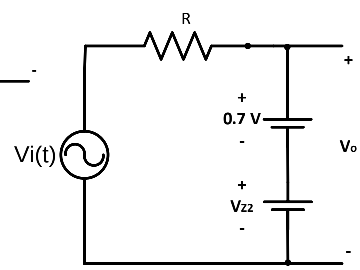
a) When $0.7V < V_i(t) < V_{Z2}$,
D1- regular diode ON
D2- regular diode OFF



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



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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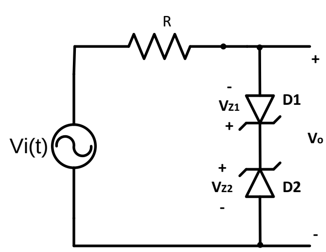
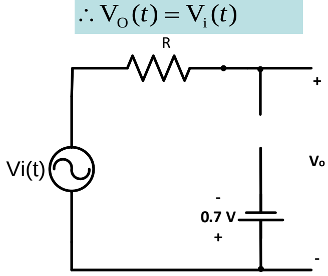
Clipper circuits using Zeners

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)

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