ENEE2360

Analog Electronics

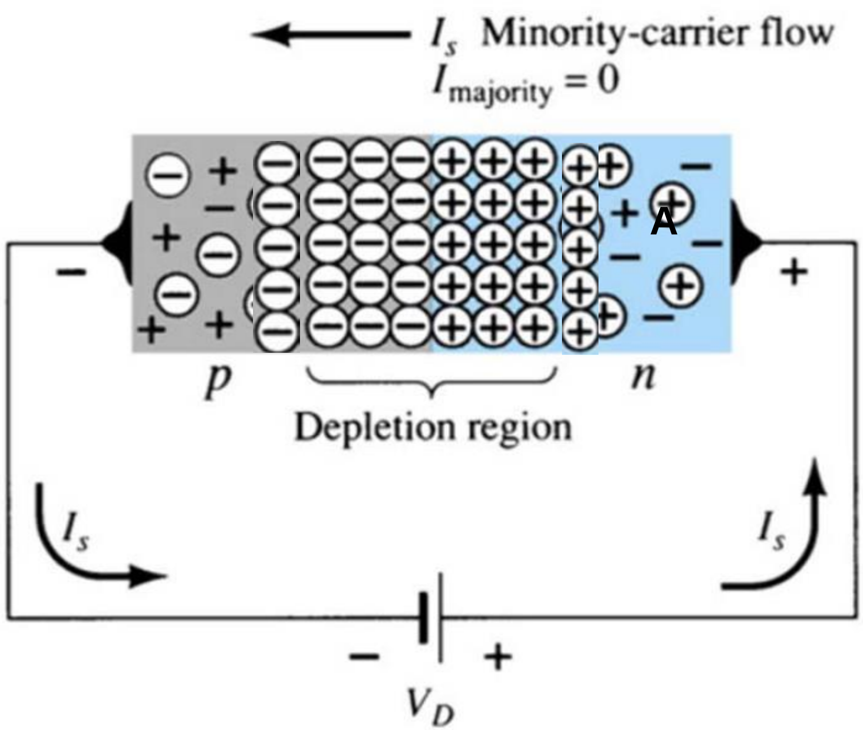
T5:
Zener Diode

INSTRUCTOR: NASSER ISMAIL

Zener Diode
Simple Voltage Regulator

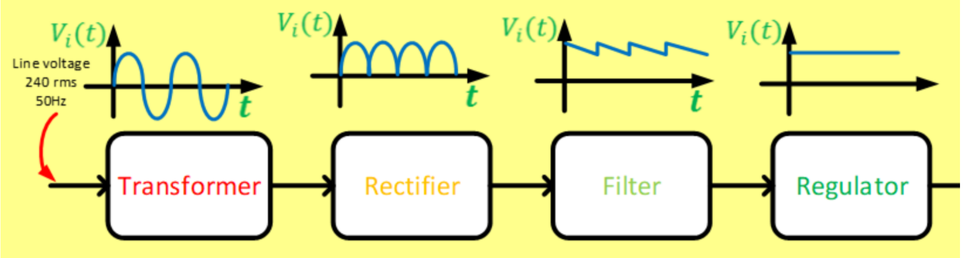
- *The Zener is used as a voltage regulator to maintain a constant dc output under variations in load current and ac line voltage*
- *It can also be used as protection device against overvoltage*
- *Analysis starts by defining state of diode followed by using appropriate model, then find unknown quantities*

Reverse bias of a pn junction Breakdown Voltage



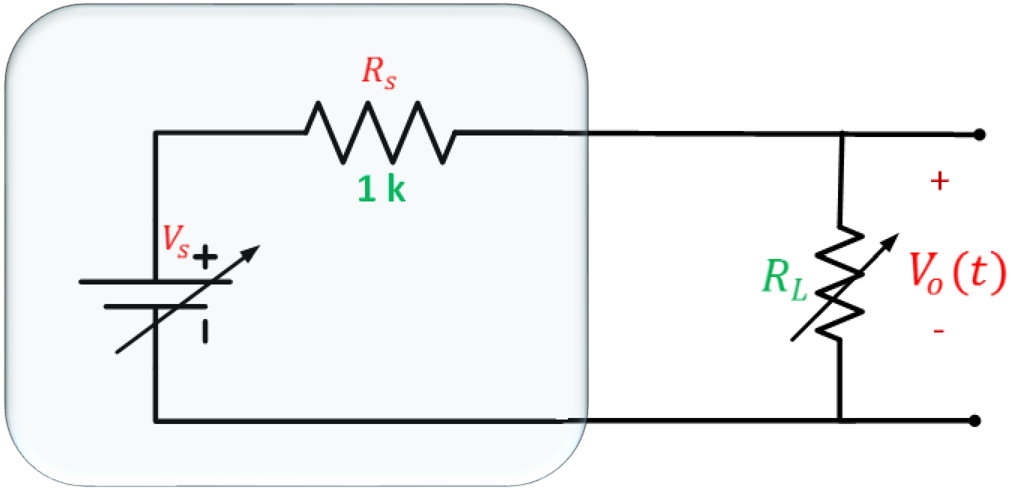
The electric field may become large enough for the covalent bond to break, causing electron-hole pairs to be created.

Regulator :

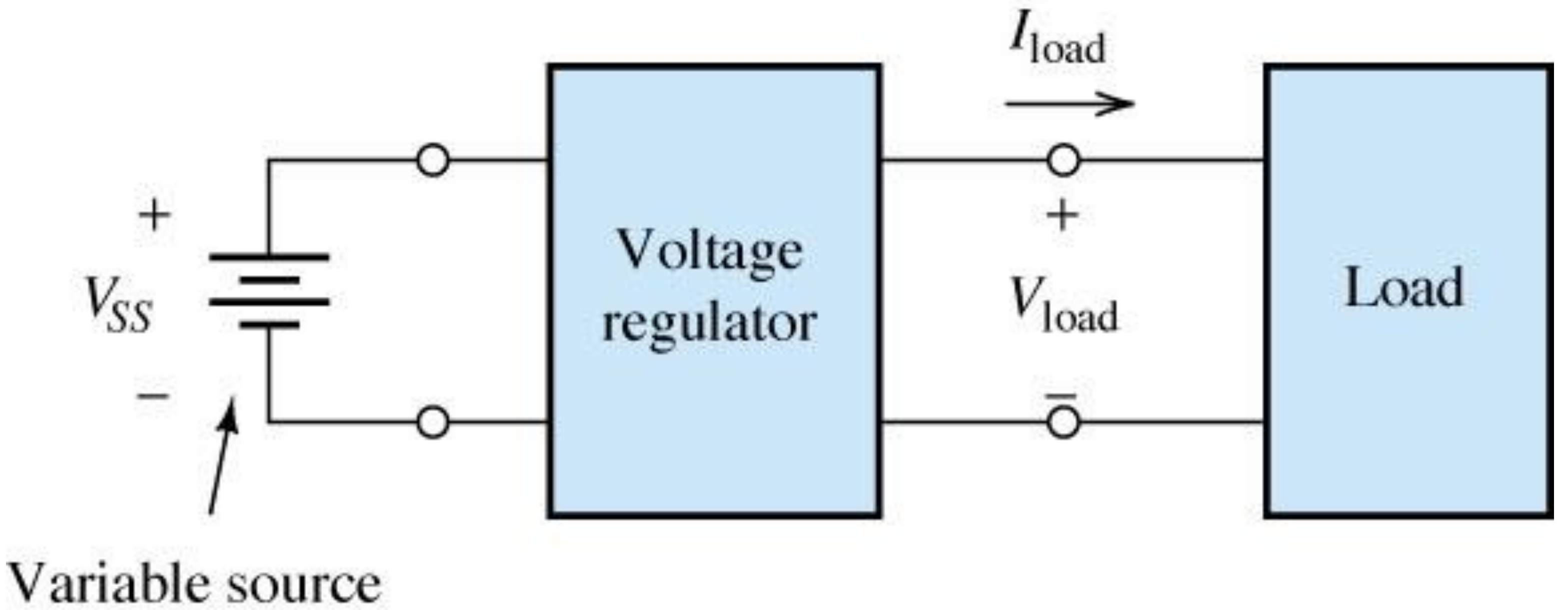


Used to maintain a constant dc output voltage under variation in the load current from the dc power supply and under variation in the ac line voltage

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

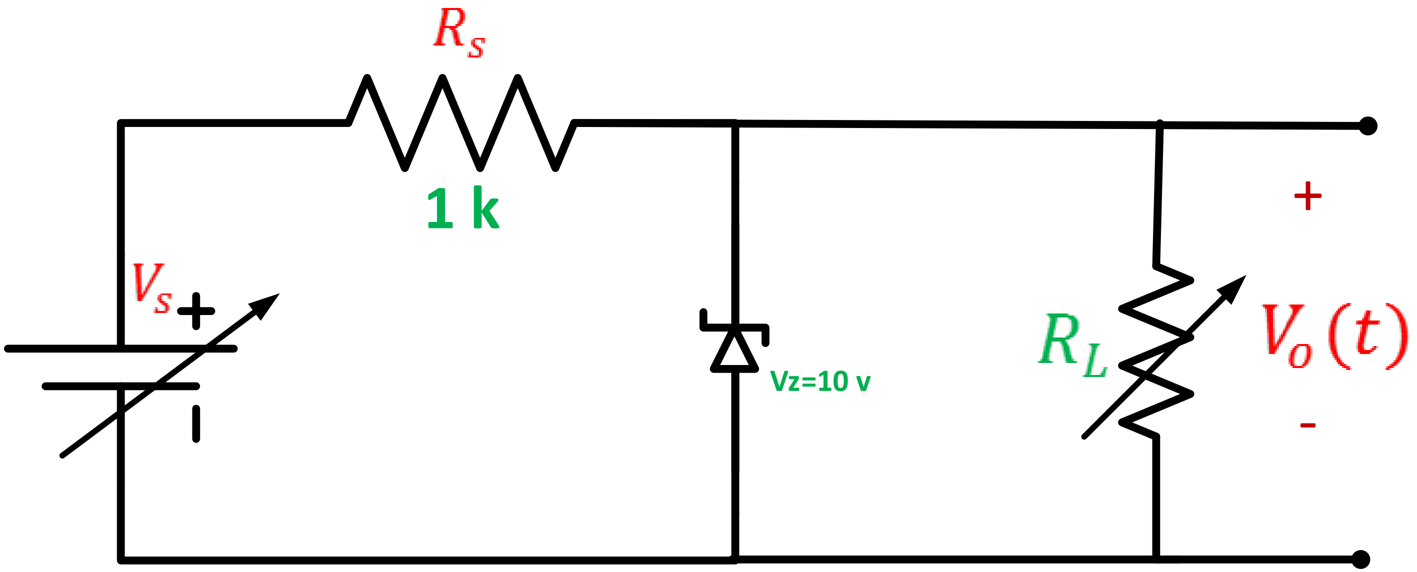


Voltage Regulator

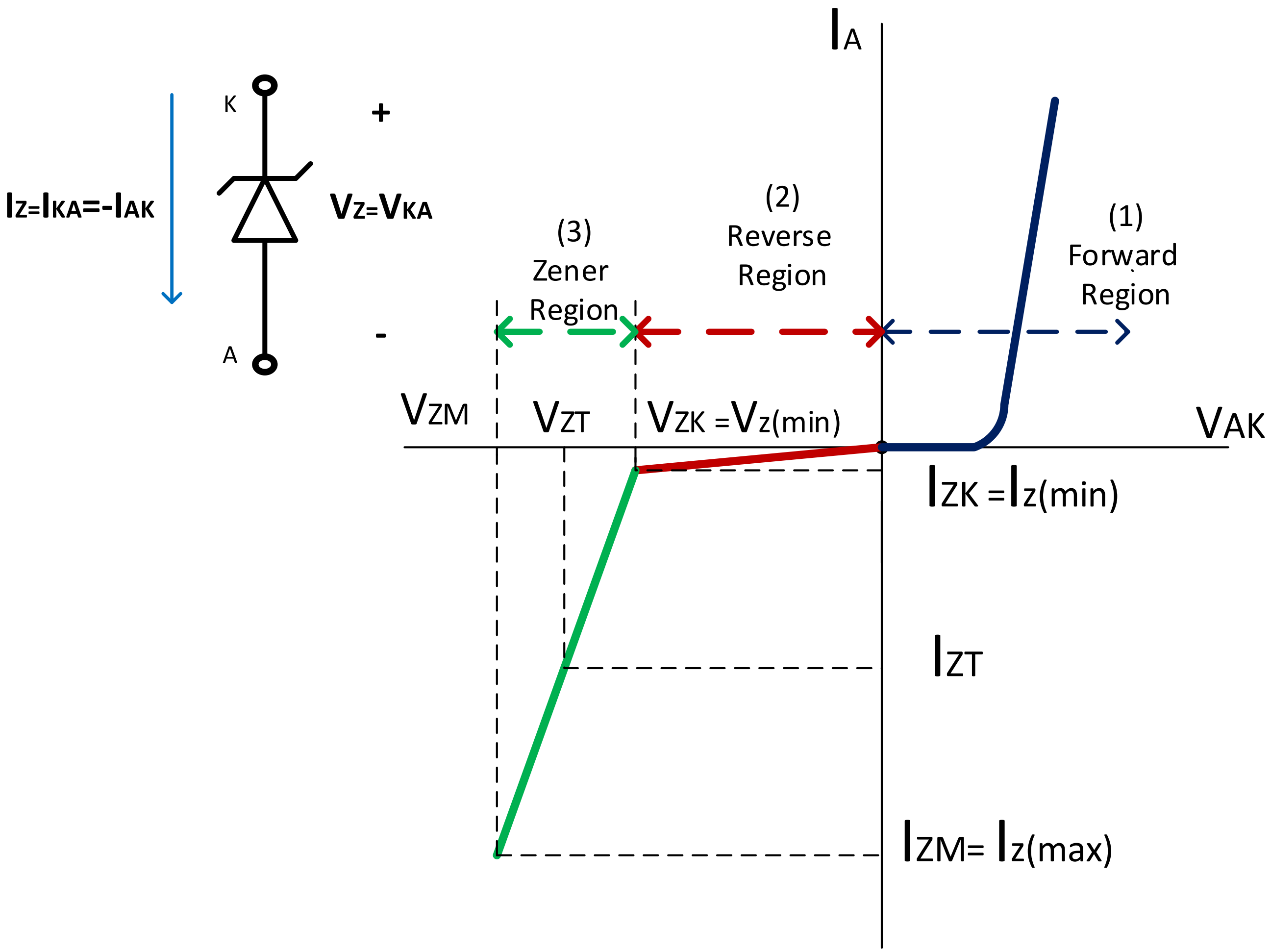


A voltage regulator supplies constant voltage to a load.

Simple voltage regulator

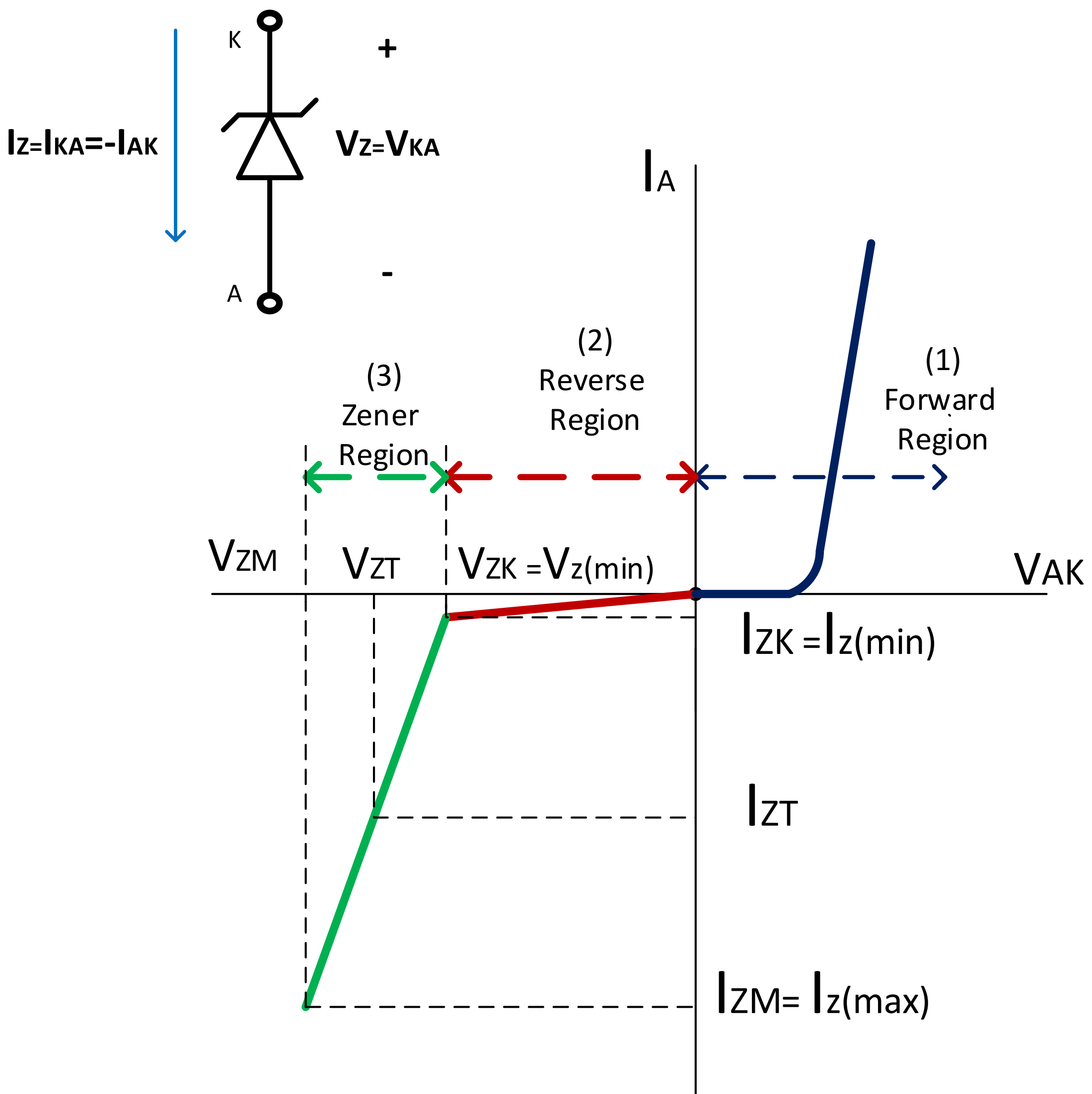


Zener Diode V-I Curve



- 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

Zener Diode Operation Regions



Region (1)

- When VAK>0 , zener acts as regular diode ON

- Region (2)

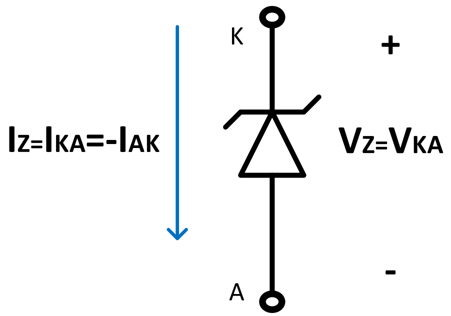
When 0 <VKA<VZK , zener acts as regular diode OFF

- 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).



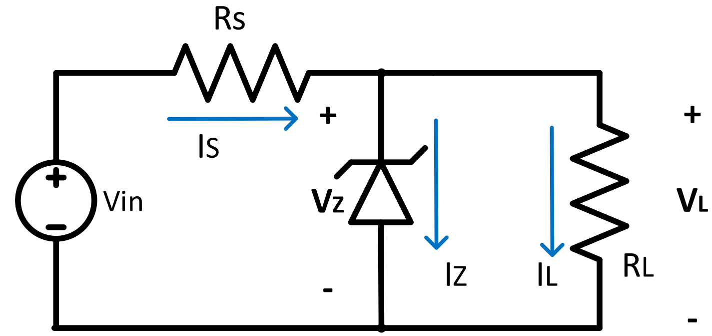
Conditions for zener diode to operate in the breakdown (Zener/ON) region When

1. Cathode is more positive than anode

2. $V_{th} \geq V_Z$

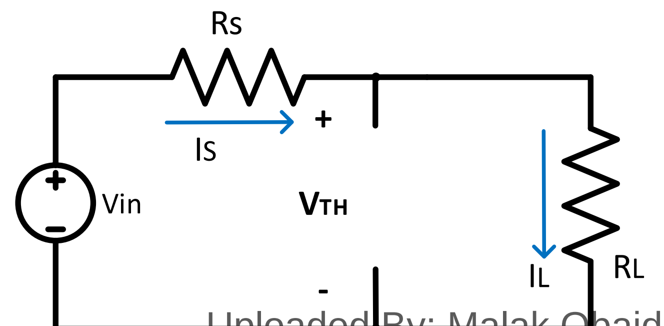
3. Iz > Iz(min)

4. Iz< Iz(max)



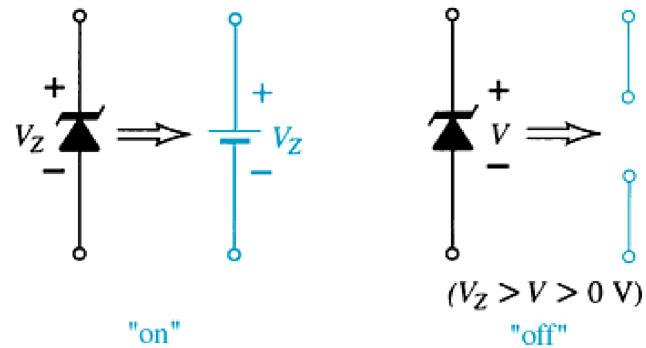
==> Voltage across the Zener is V_Z

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

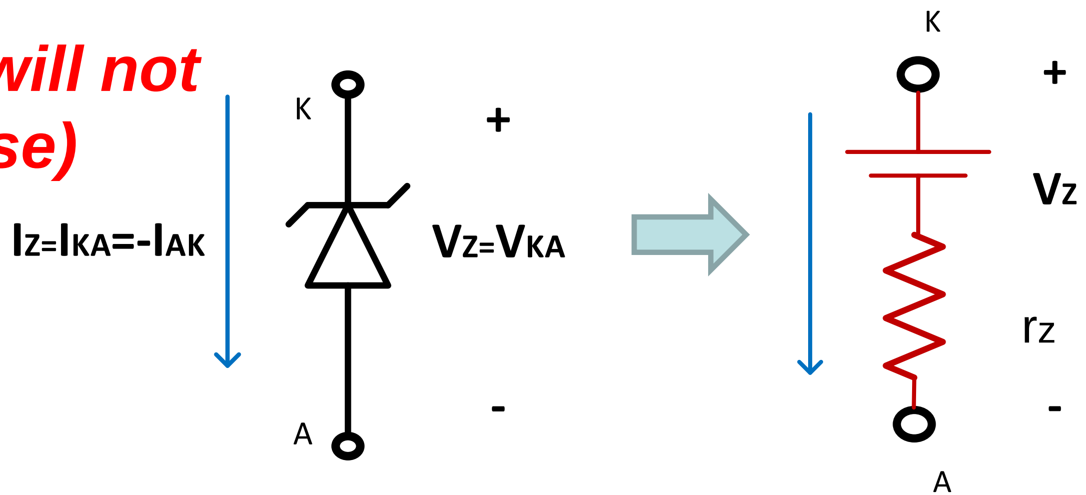


Zener Diode Models

1. Ideal Model



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



Fixed Vin, Variable RL

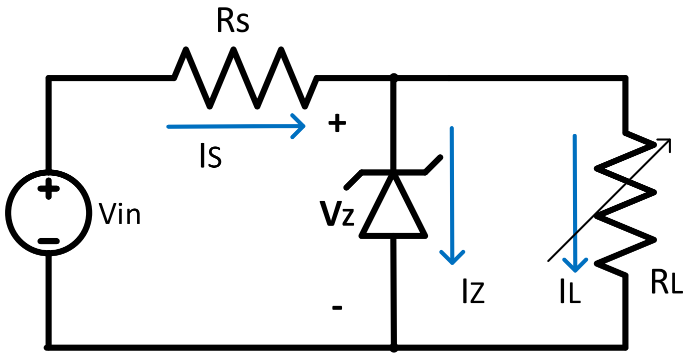
- *Due to the value of Vz, there is specific values of RL (IL) that ensure the zener is in the ON (regulation) state*
- *Too small values of RL can result in zener being OFF*

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

$$\mathbf{V_{th} \geq V_Z}$$

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

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



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

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

$$\Downarrow$$

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

Example

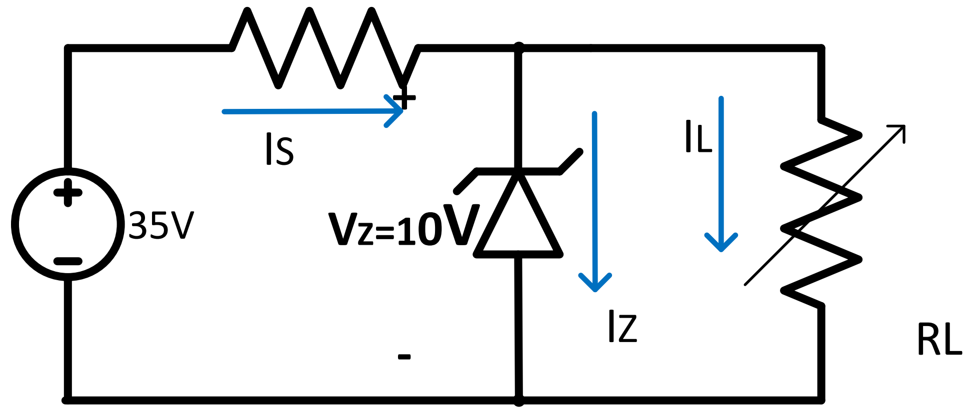
Given the following values of R_L, find the mode of operation of the zener and the voltage V_L

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) $R_L = 0.1\,k\Omega$

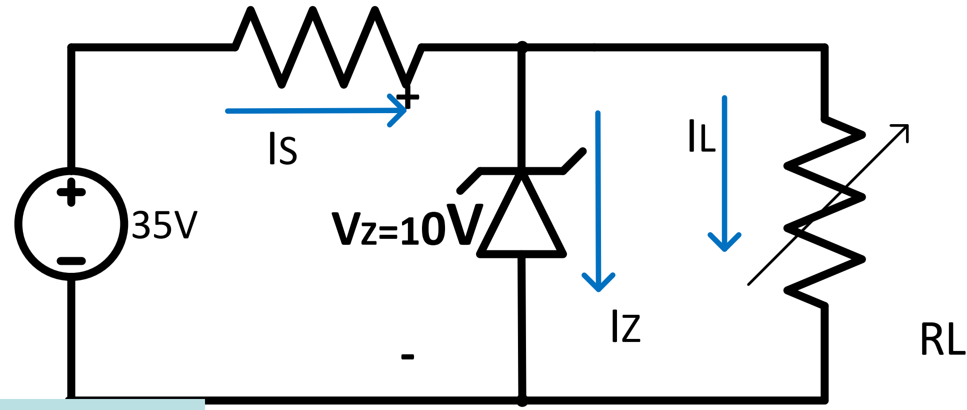
using ideal model

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

Zener works in region 2, it acts as open circuit

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

Example



$$\text{b) } R_L = 0.5\,\text{k}\Omega$$

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

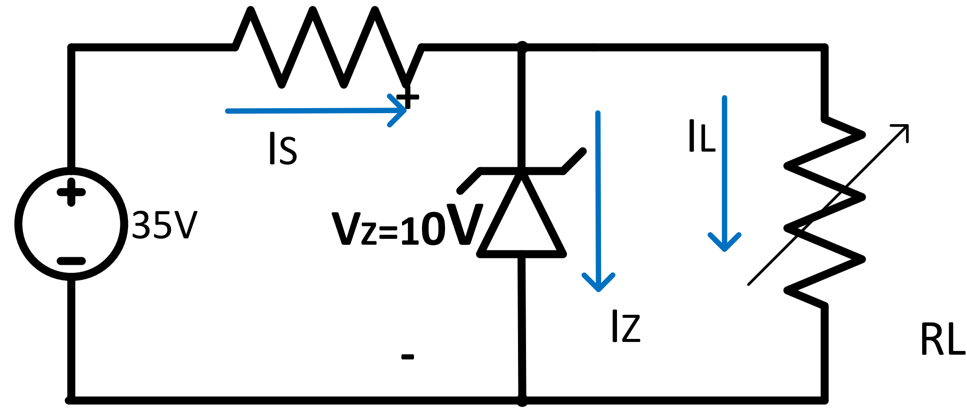
$$V_L = V_Z = 10\text{ V}$$

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

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

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

Example



$$\text{c) } R_L = 5\,k\Omega$$

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

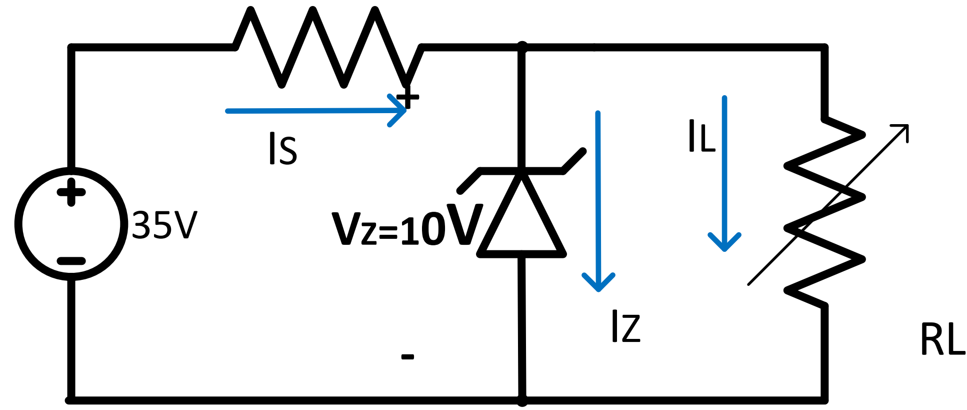
$$V_L = V_Z = 10\,V$$

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

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

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

Example



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

using ideal model

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

$$V_{th} > V_Z$$

Zener works in region 3, it works as voltage regulator

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

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

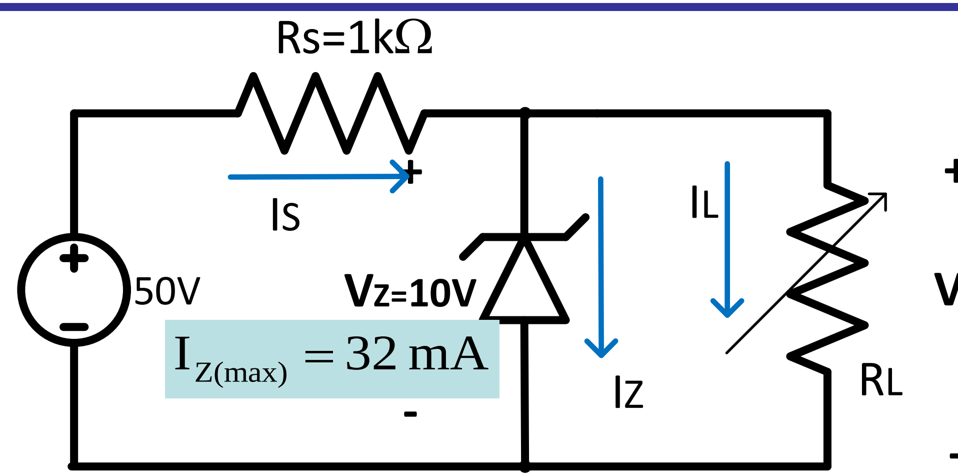
$$I_L = \frac{V_L}{R_L} = \frac{10}{\infty} = 0$$

$$I_Z = I_S - I_L = 25\text{ mA}$$

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) $P_{Z(\max)} = V_Z . I_{Z(\max)} = 10\text{ V} \ .\ 32\text{ mA} = 320\text{ mW}$

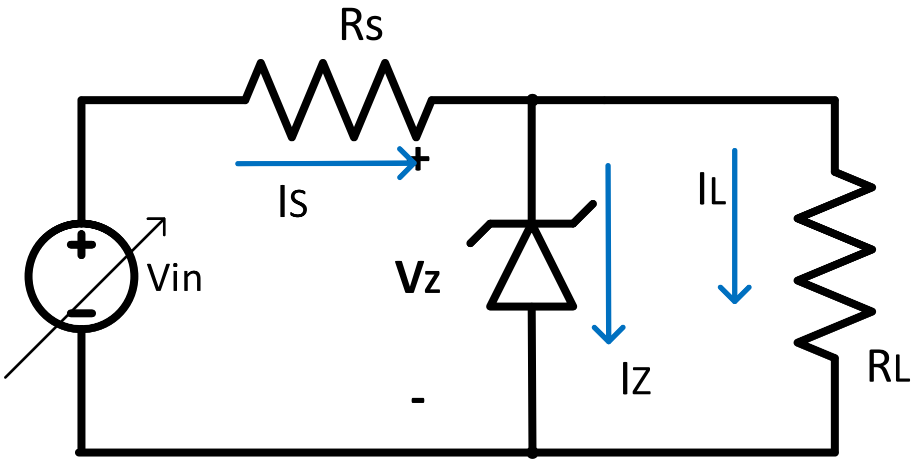
The zener diode is chosen with power rating $\ge P_{Z(\max)}$

Fixed RL, Variable Vin

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

If Iz(min) =0

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



If Iz(min) > 0

$$V_{in(\min)} = I_{s(min)}.Rs + V_Z$$

$$I_{S(\min)} = I_{Z(min)} + I_L$$

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

$$I_S = I_Z + I_L$$

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

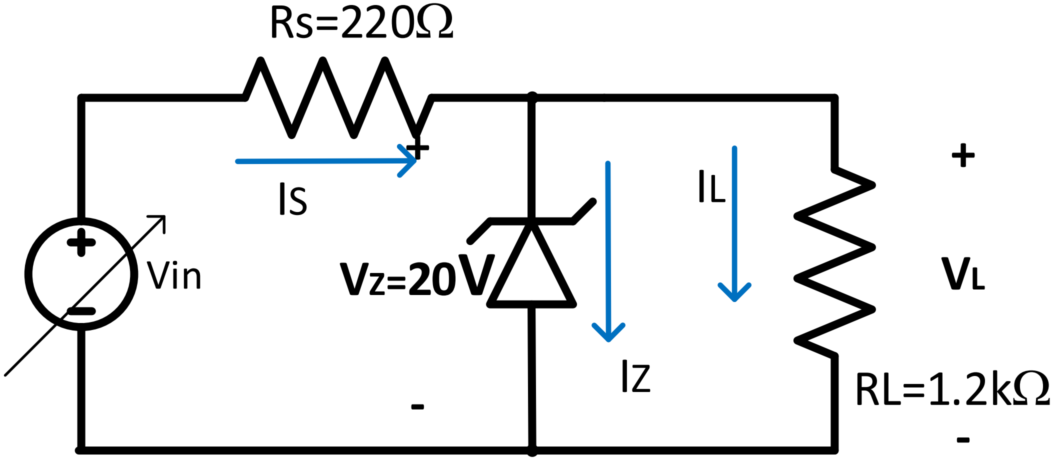
$$V_{i(\max)} = I_{S(\max)}.R_S + V_Z$$

$$\Downarrow$$

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

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

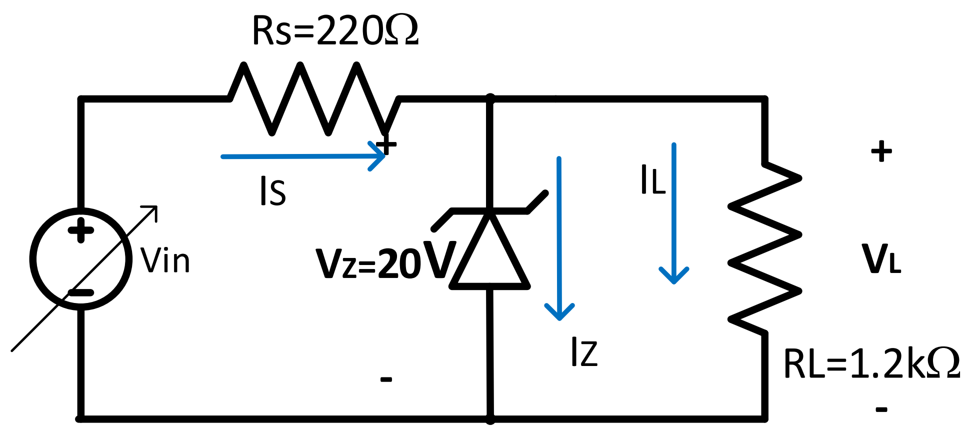
Find range of acceptable Rs in the voltage regulator

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

Worst Case : the smallest value of $(I_S - I_L)$

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

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



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

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

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

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

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

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

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

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?

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

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

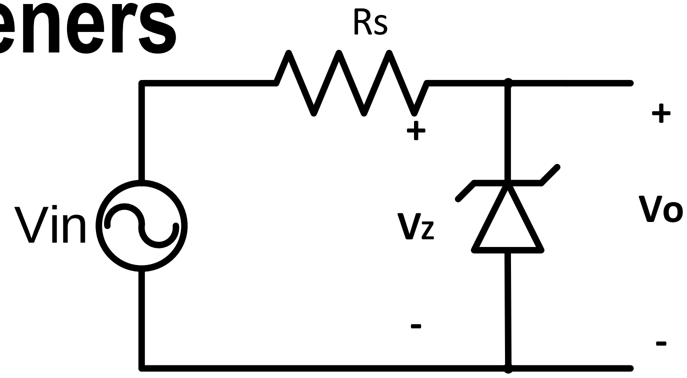
and

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

$200\,\Omega \geq R_S \geq 50\,\Omega$

let $R_S = 100\,\Omega$

Clipper circuits using Zeners



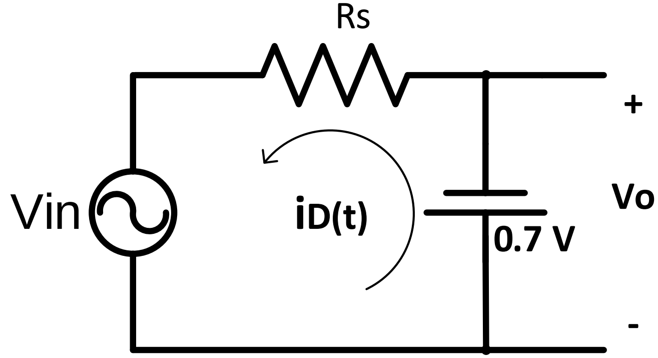
a) When $V_i(t) < -0.7$ V, Zener works in region (1) as regular diode ON

$$0.7 + i_D(t).R + V_i(t) = 0$$

$$i_D(t) = \frac{-V_i(t) - 0.7}{R} > 0$$

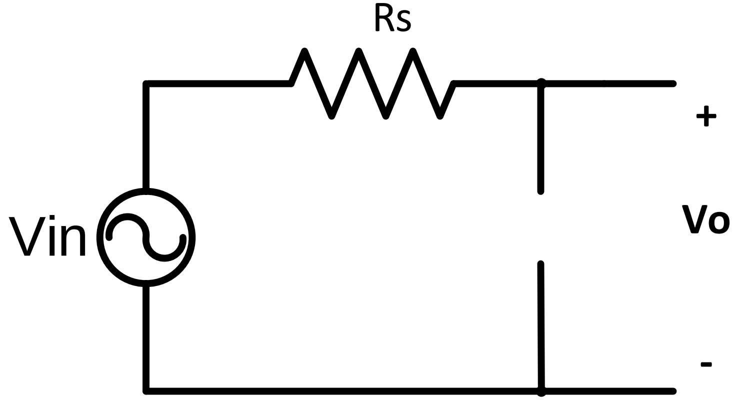
$$V_i(t) < -0.7$$

$$\therefore V_O(t) = -0.7$$



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

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



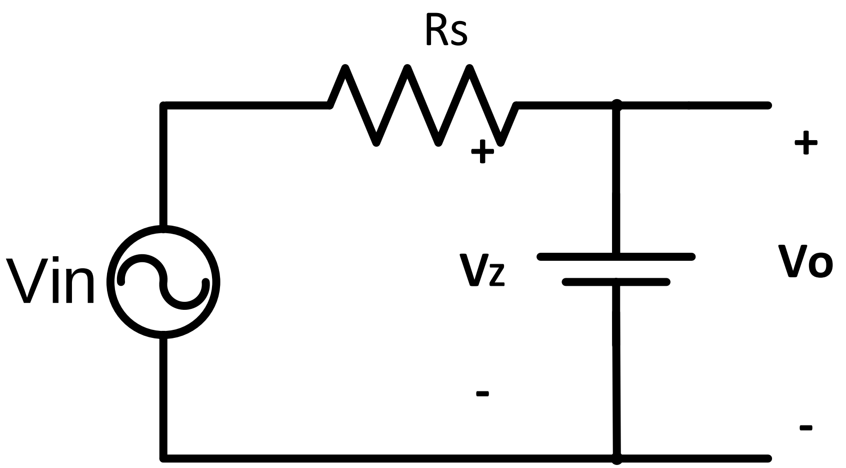
c) When $V_i(t) > V_Z$, Zener works in region (3) as voltage regulator

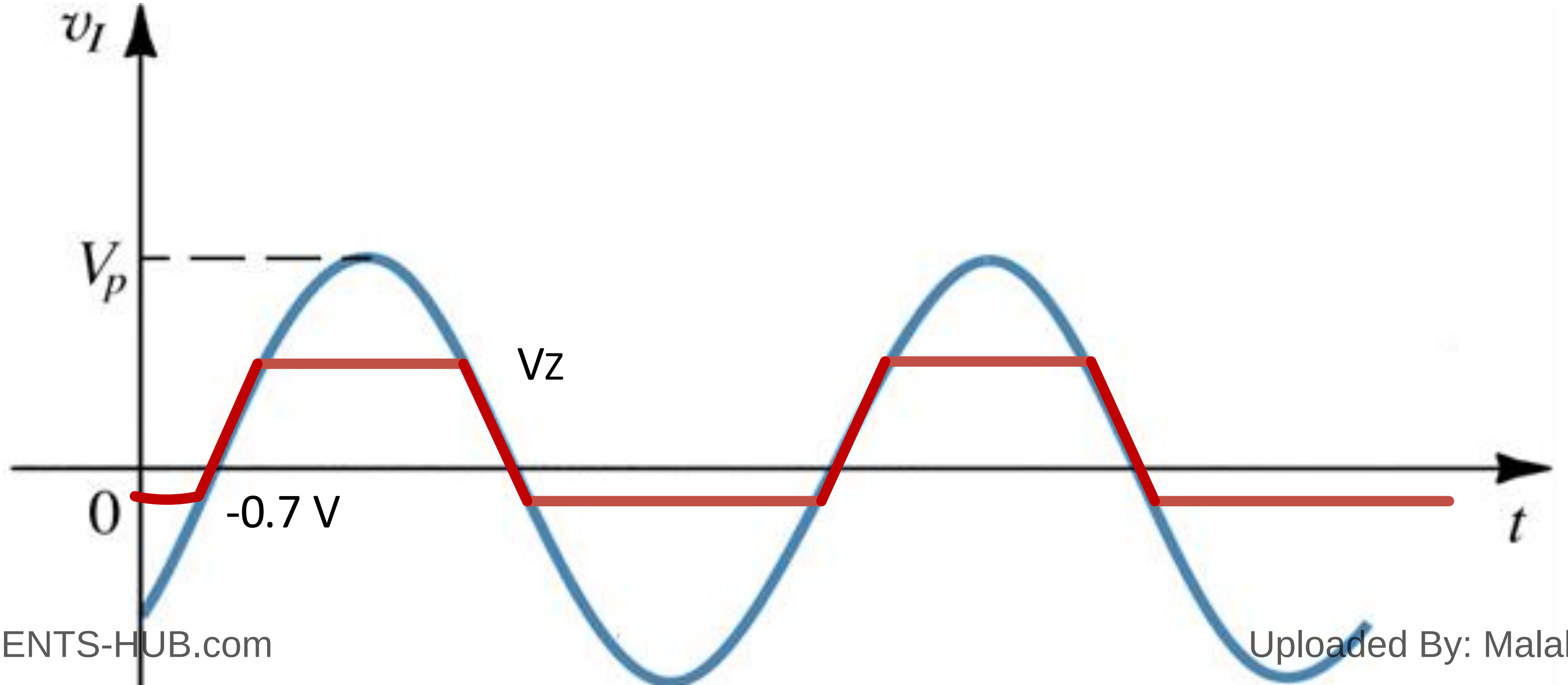
$$\therefore V_O(t) = V_Z$$

Clipper circuits using Zeners

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

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





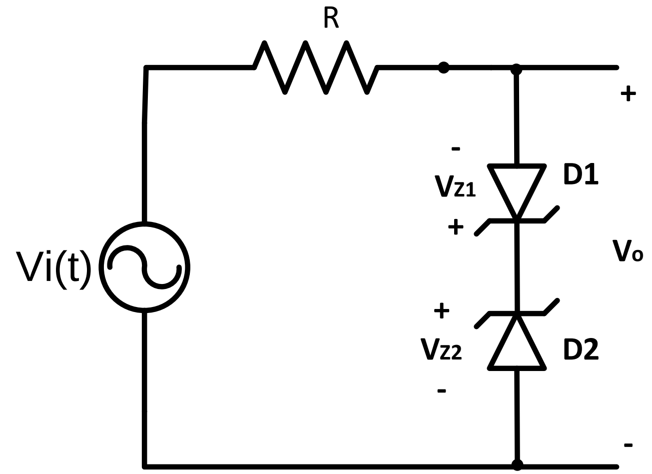
Clipper circuits using Zeners

Find and sketch $V_o(t)$

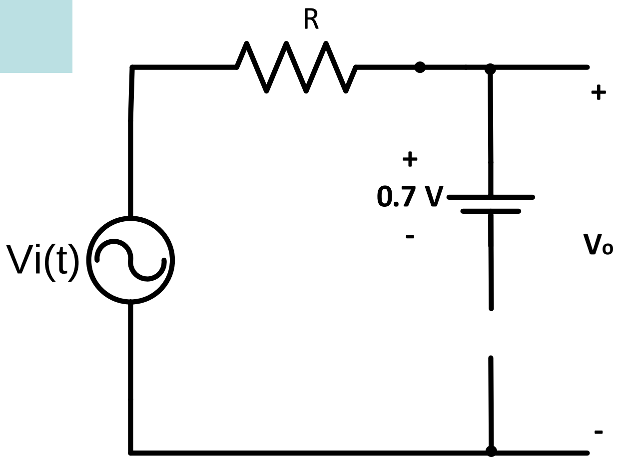
a) When $0.7V < V_i(t) < V_{Z2}$,

D1- regular diode ON

D2- regular diode OFF



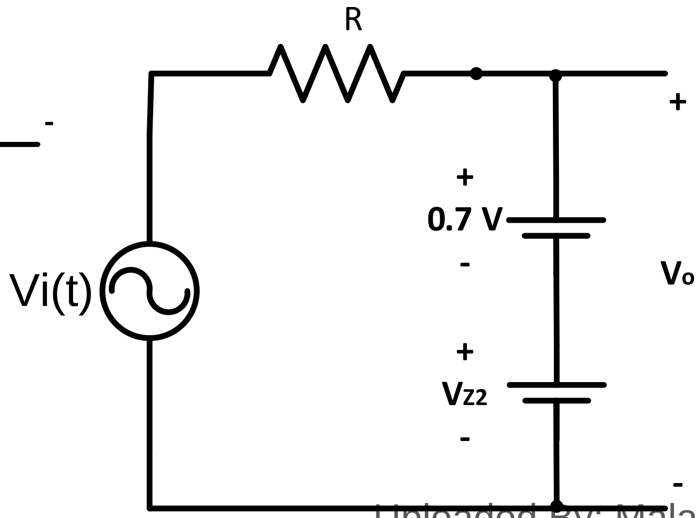
$$\therefore V_O(t) = V_i(t)$$



b) When $V_i(t) > V_{Z2}$

D1 – ON (region 1)

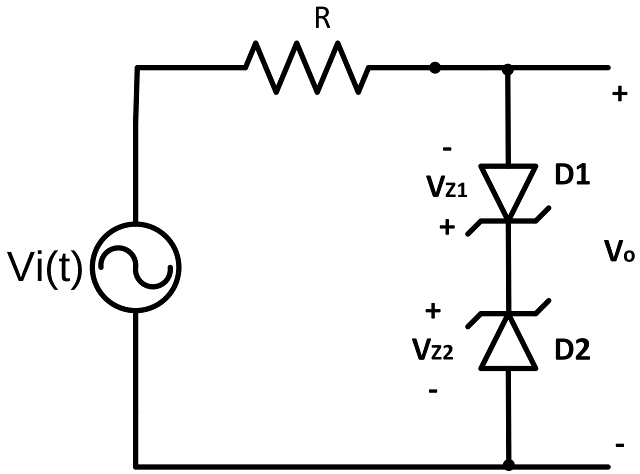
D2- Zener ON (region 3)



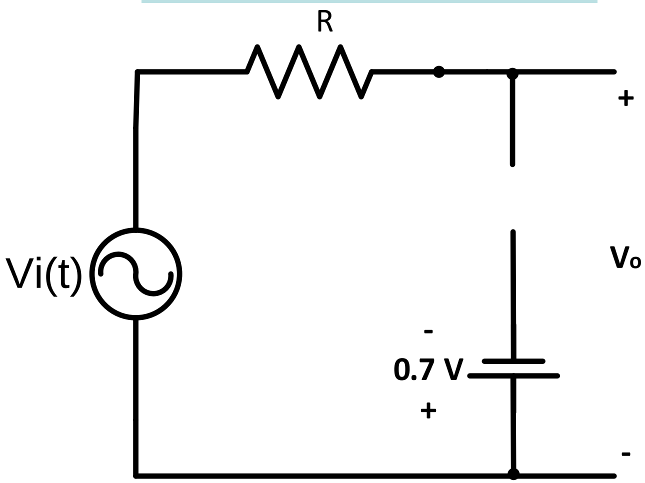
$$\therefore V_O(t) = V_{Z2} + 0.7$$

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)

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