L8
26/7/2021

ENEE2360

Analog Electronics

T5:
Zener Diode

INSTRUCTOR: NASSER ISMAIL

Zener Diode
Simple Voltage Regulator

?

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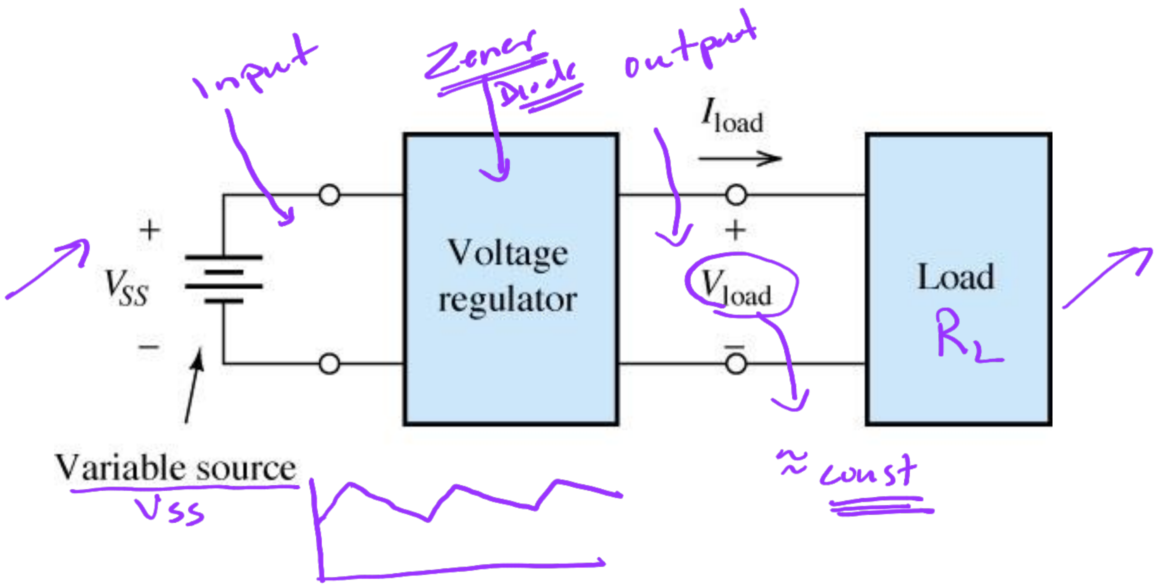
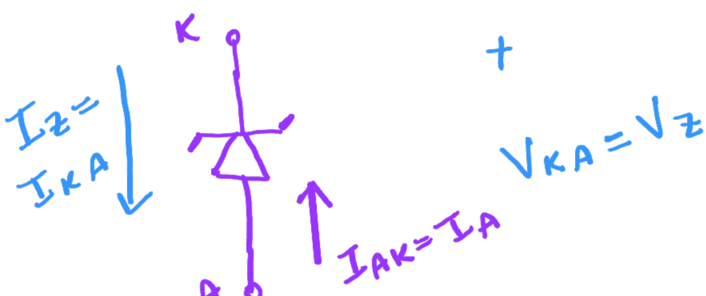
Keep

- *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*

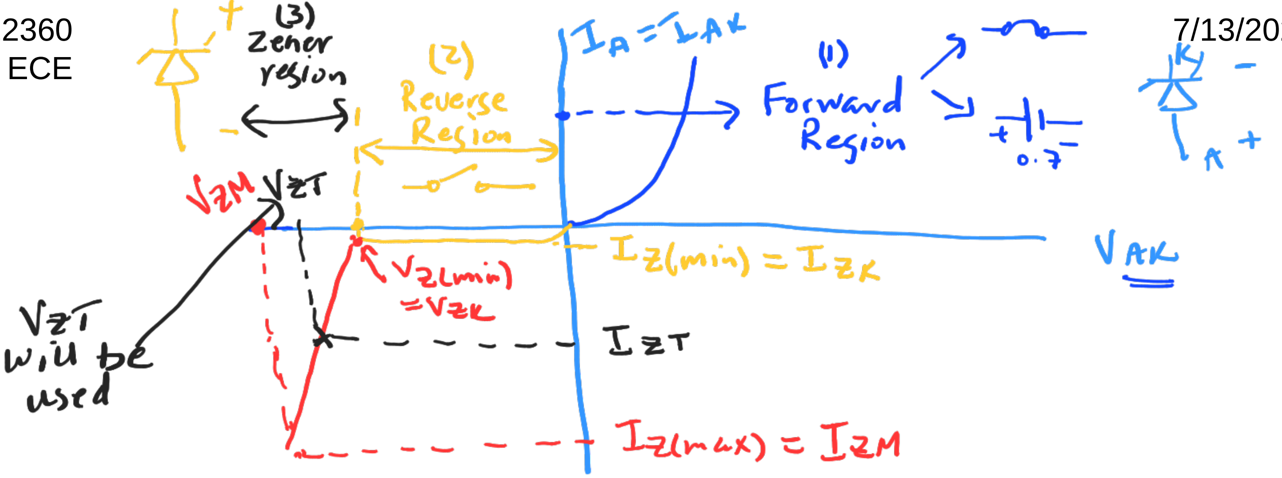
Voltage Regulator



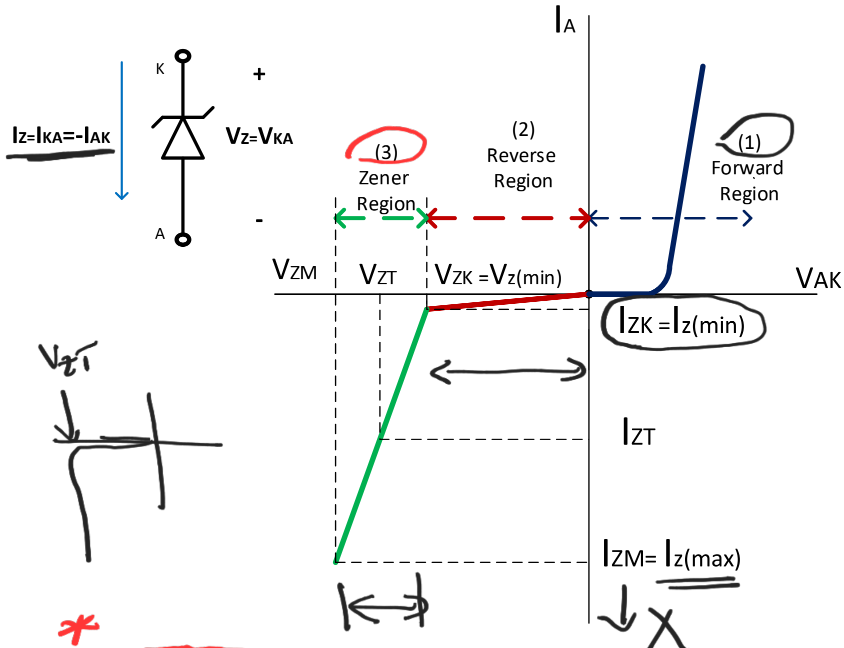
A voltage regulator supplies constant voltage to a load.



$I_Z = I_{KA} = -I_{AK}$



Zener Diode V-I Curve



- In data sheet , we have I_{ZT}, V_{ZT}
- Zener currents I_Z will be assumed positive if passing from cathode to Anode
- If $I_Z < I_{ZK}$ zener will act as an open circuit region(2)
- If $I_Z > I_{Zmax}$ zener will damaged

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- If $I_{ZK} < I_Z < I_{Zmax}$ zener will be in voltage regulation (zener) region

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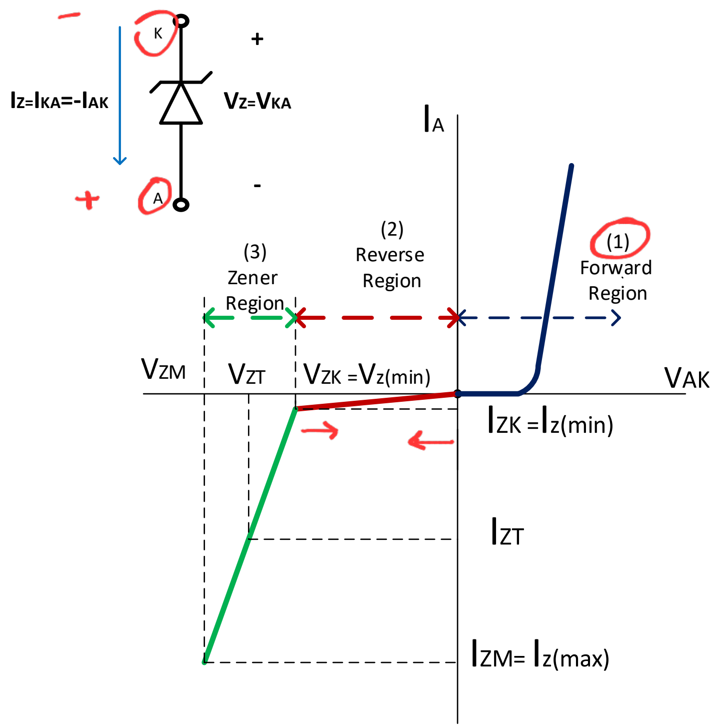
Zener Diode Operation Regions



Region (1)
- When VAK>0 , zener acts as regular diode ON → short
→ 0.7

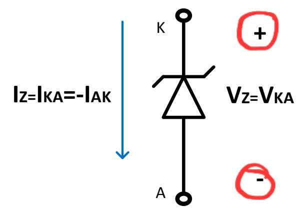
- Region (2)
When 0 <VKA<VZK , zener acts as regular diode OFF →

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

? Model

Zener Diode
Operation & Models

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

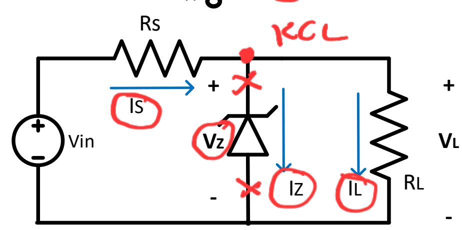


Model ??

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

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

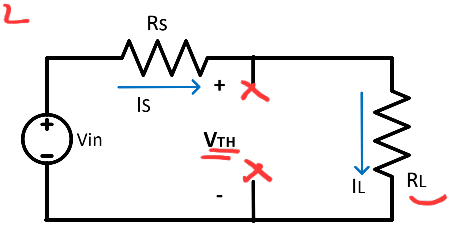
KCL



$I_S = I_Z + I_L$

==> 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

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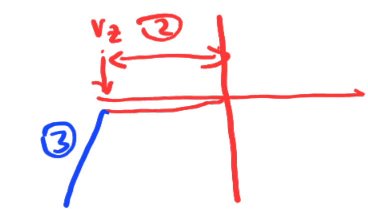
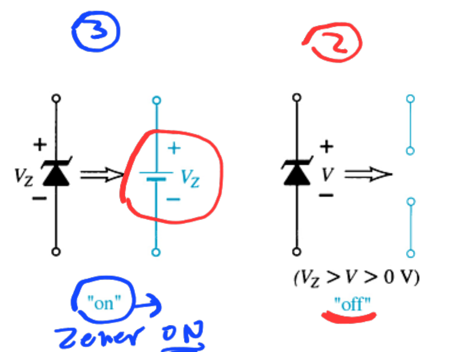
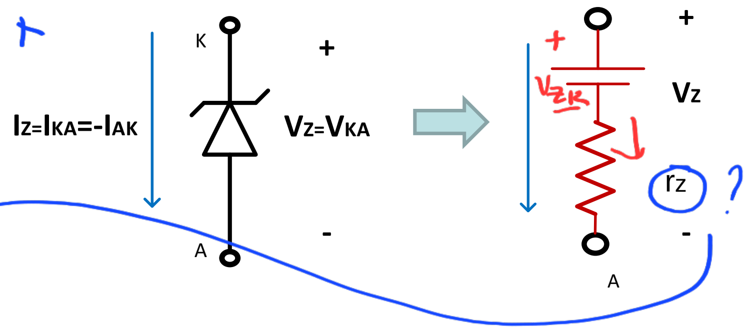
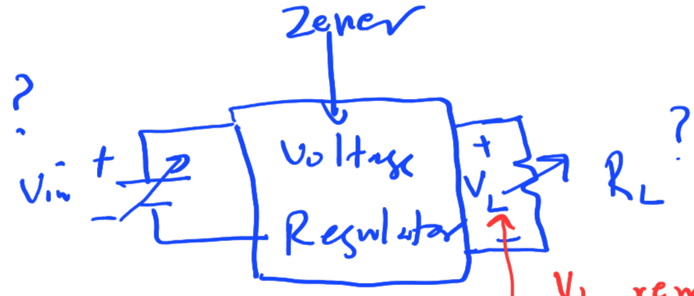




2. Simplified Model

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





$? \le R_L \le ?$

$? \le V_{in} \le ?$

V_L remains almost constant regardless of V_{in} & R_L change within reasonable limits

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Fixed Vin, Variable RL

$R_{L(min)} \le R_L \le R_{L(max)}$

$\leftarrow I_{L(max)}$

$\downarrow I_{L(min)}$

- *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*

1)
$$V_L = V_Z = \frac{R_L}{R_L + R_S} V_{in}$$

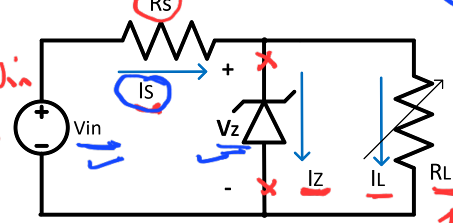
$V_{th} \ge V_Z$

$V_{th} = \frac{R_L}{R_L + R_S} \cdot V_{in}$

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

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

$I_L = \frac{V_L}{R_L}$



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

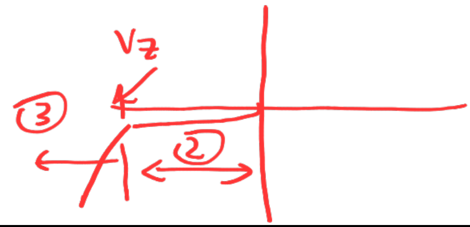
$$I_{L(\min)} = I_S - I_{Z(\max)}$$
$$\Downarrow$$
$$R_{L(\max)} = \frac{V_Z}{I_{L(\min)}} = V_L$$

$I_S = I_Z + I_L$

$I_L = I_S - I_Z$

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

$? \rightarrow I_S$



Example

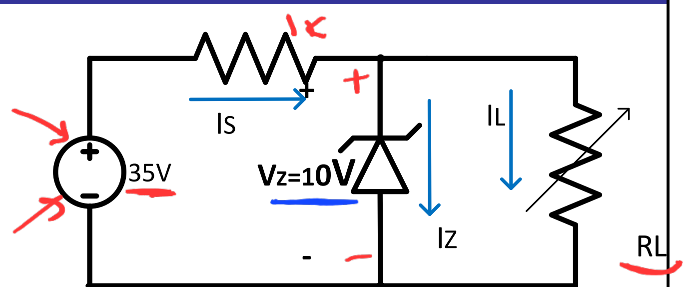
Given the following values of R_L, find the mode of operation of the zener and the voltage V_L, I_L, I_Z

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

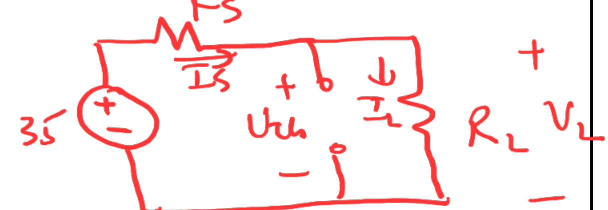
a) $R_L = 0.1\,k\Omega$

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)



1) $V_{th} = \frac{R_L}{R_L + R_s} \cdot V_{in}$

$V_{th} = \frac{0.1k}{0.1k + 1k} \cdot 35 = 3.18 < V_z$

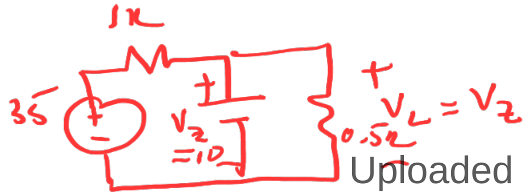
region 2 → open circuit

$\therefore V_L = V_{th} = 3.18\,V$

$I_Z = 0,\ I_L = \frac{3.18}{0.1k} = I_S$

2) $V_{th} = \frac{0.5k}{0.5k + 1k} \cdot 35$

$= 11.67 > V_Z = 10 \rightarrow$ region 3



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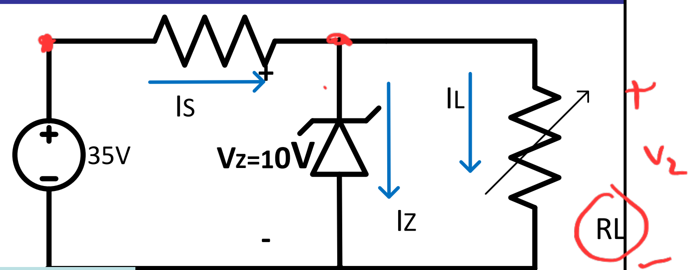
Example



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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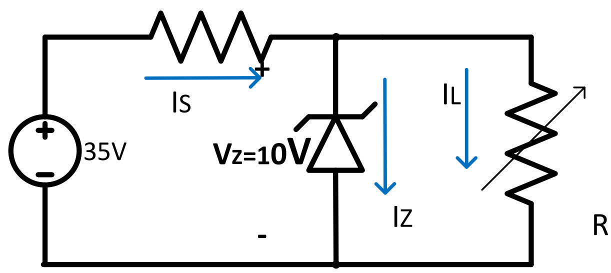
Example



c) $R_L = 5\ k\Omega$

using ideal model

$$V_{th} = \frac{R_L}{R_L + R_S} V_{in} = \frac{5}{5+1} 35\ V = 29.17\ V$$ $> V_z = 10$

$V_{th} > V_Z$

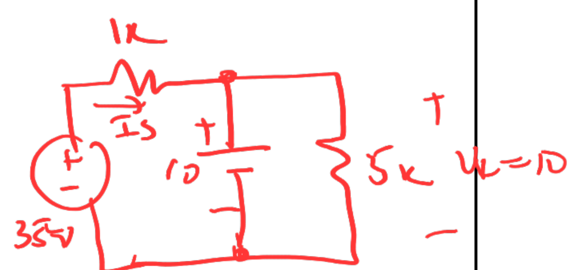
Zener works in region 3, it works as voltage regulator

$V_L = V_Z = 10\ V$

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

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

$I_Z = I_S - I_L = 23\ mA$



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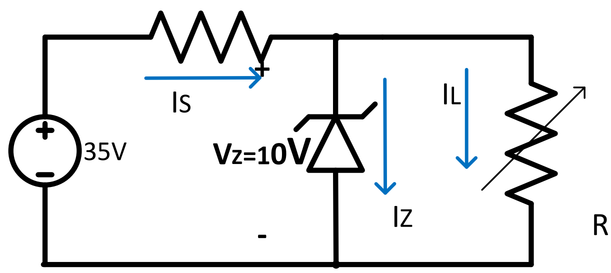
Example



d) $R_L = \cancel{5\,k\Omega}\ \infty$

using ideal model

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

$$V_{th} > V_Z$$

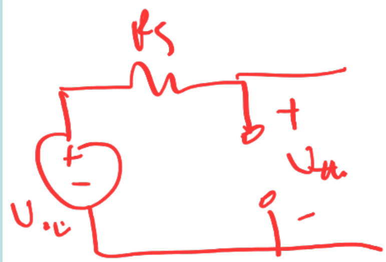
Zener works in region 3, it works as voltage regulator

$$V_L = V_Z = 10\ V$$

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

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

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



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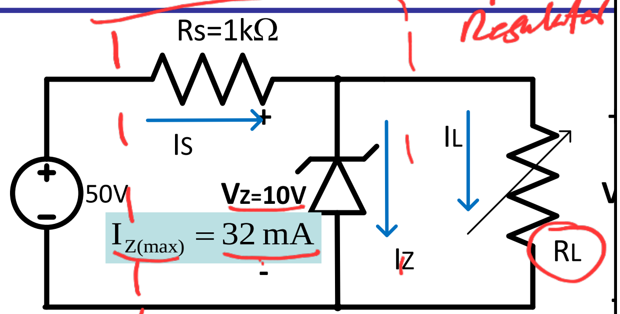
Voltage Regulator

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 $P_Z = V_Z \cdot I_Z$



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

SOLUTION

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

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

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

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

$$\boxed{250\,\Omega \le R_L \le 1.25\,k\Omega}$$

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

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

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

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

$$\Downarrow$$

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

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 $\ge P_{Z(max)}$

$40\text{mA} \ge I_L \ge 8\text{ mA}$

$\frac{10V}{250}$ $\frac{10V}{1.25k}$

End of L8

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L9
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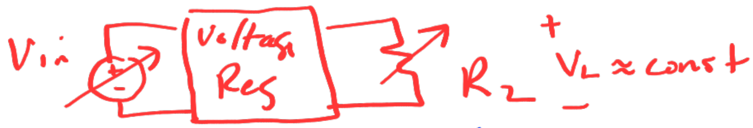


Fixed RL, Variable Vin

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

? ≤ Vin ≤ ?

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

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

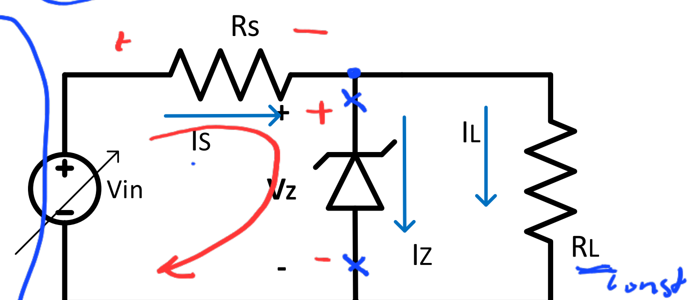
$$I_S = I_Z + I_L$$

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

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

$$\Downarrow$$

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



$$V_{th} = \frac{R_L}{R_L + R_S} \cdot V_{in} \geq V_Z$$

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

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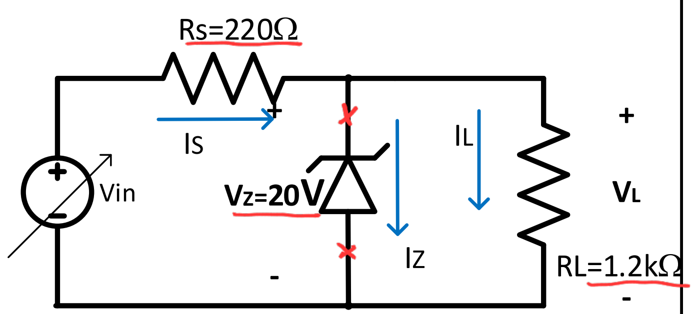
Example

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



1)

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

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

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

$$I_S = I_Z + I_L$$

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

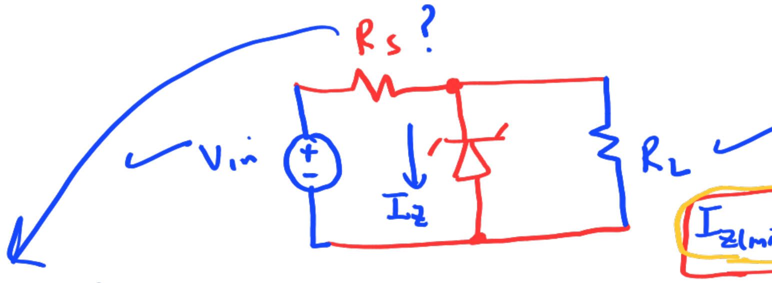
$$I_L = \frac{V_L}{R_L} = \frac{20\text{ V}}{1200\,\Omega} = 16.67\text{ mA}$$

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

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

$= I_{s(max)} \cdot R_s + V_Z$

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



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

How to Calculate Rs ? → current limiting Resistor

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

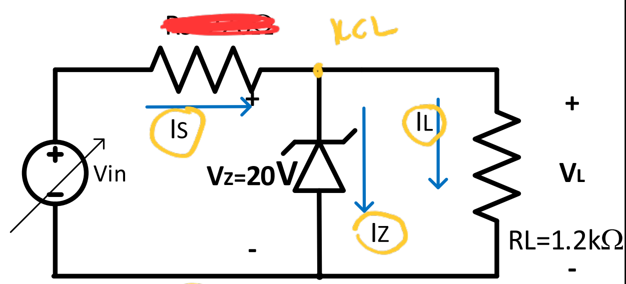
Worst Case : the smallest value of $(I_S - I_L)$ must be always higher than $> I_{Z(min)}$

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

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

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

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



$I_S = \frac{V_{in} - V_Z}{R_S}$

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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 $I_{Z(max)}$

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

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

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

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

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?

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

Solution

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

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

$$\boxed{200\ \Omega \geq R_S \geq 50\ \Omega}$$

let $R_S = 100\ \Omega$

Variation of Vz (using simplified model)

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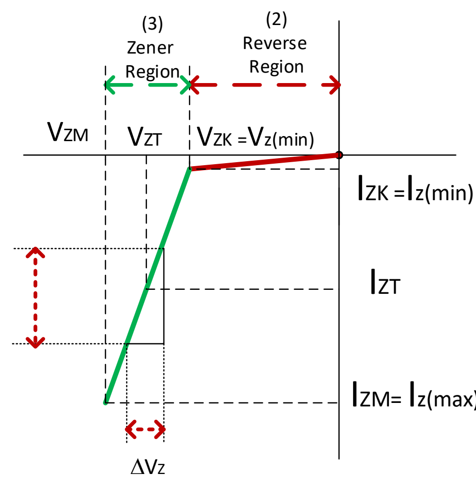
$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

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

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



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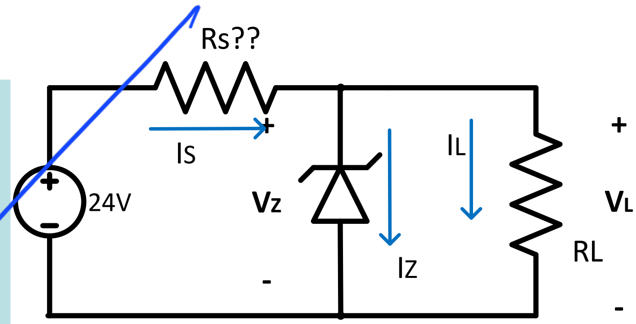
Example



If $V_{ZT} = 15V$ at $I_{ZT} = 17mA$

& $r_{ZT} = 14\,\Omega$

$I_{ZK} = 0.25\,mA$

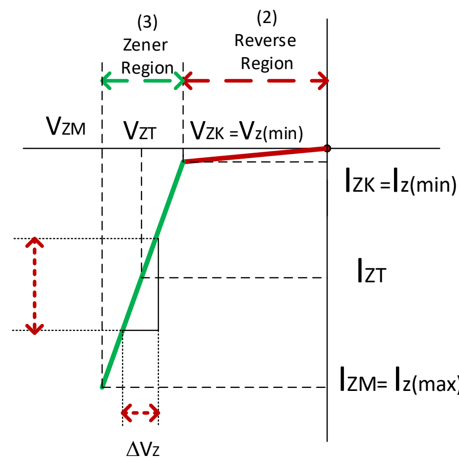
$P_{Zmax} = 1\,Watt$

Find:

1) Minimum and Maximum Values of Vz

2) Value of R_S

3) Value of $R_{L(min)}$



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

$$V_{Z(max)} = V_{ZM} = V_{ZT} + \Delta I_Z\,.\,r_Z$$

$$= V_{ZT} + (I_{Z(max)} - I_{ZT})\,.\,r_Z$$

$$= 15 + (66.7\text{-}17)\,mA\,(14\,\Omega) = 15.7\ V$$

$$V_{Z(min)} = V_{ZK} = V_{ZT} - \Delta I_Z\,.\,r_Z$$

$$= V_{ZT} - (I_{ZT} - I_{Z(min)})\,.\,r_Z$$

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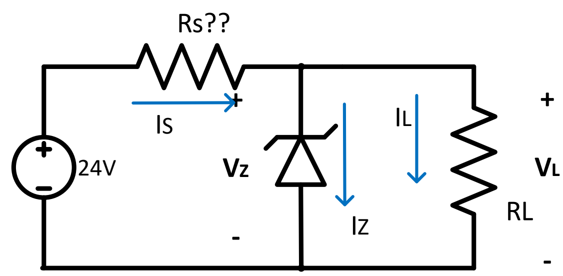
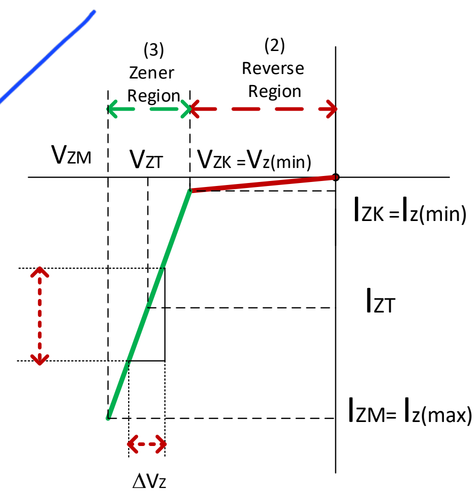
Example



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

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 $\Rightarrow$

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

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

we choose $R_S = 124\Omega$

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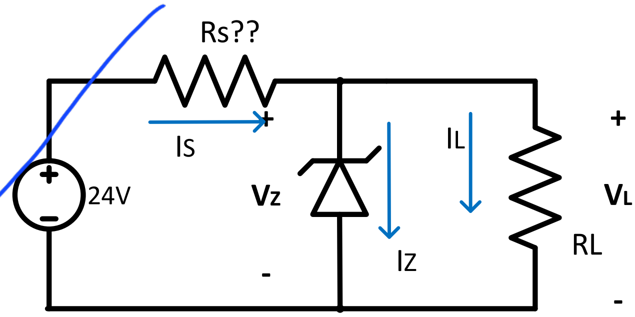
Example

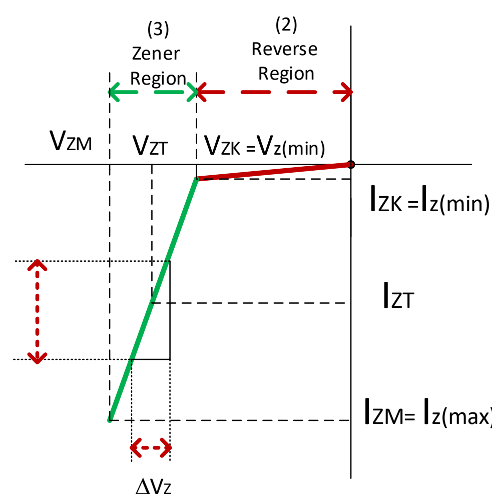
$3)R_{L(min)} \Rightarrow I_{L(max)}$

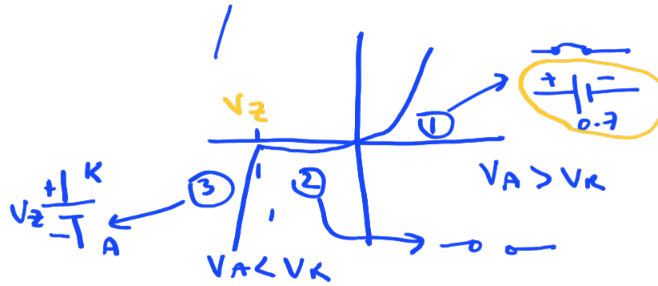
$I_{L(max)} = I_S - I_{L(min)}$

$= 66.7\ mA - 0.25\ mA = 66.45\ mA$

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







Clipper circuits using Zeners

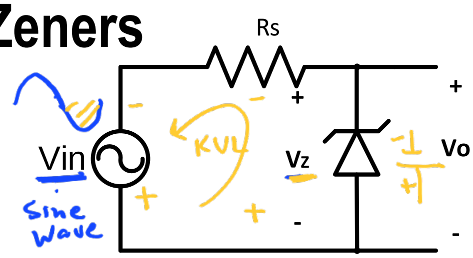
a) When $V_i(t) < -0.7$ V, Zener works in region (1) as regular diode ON

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

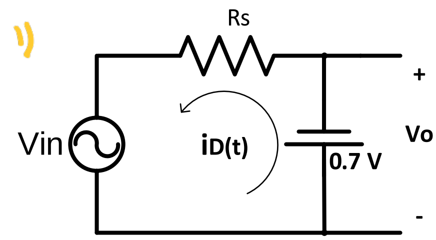
$$i_D(t) = \frac{-V_i(t) - 0.7}{R} > 0$$

$$V_i(t) < -0.7$$

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



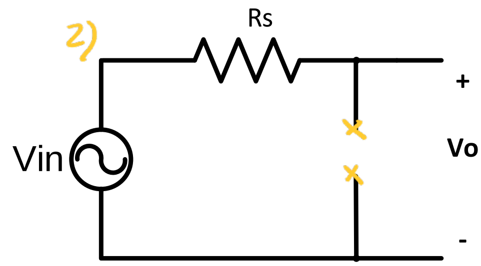
1)



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

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

2)



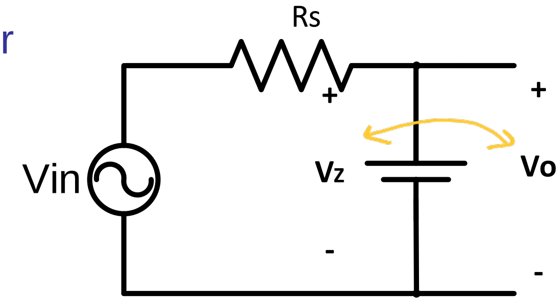
c) When $V_i(t) > V_Z$, Zener works in region (3) as voltage regulator

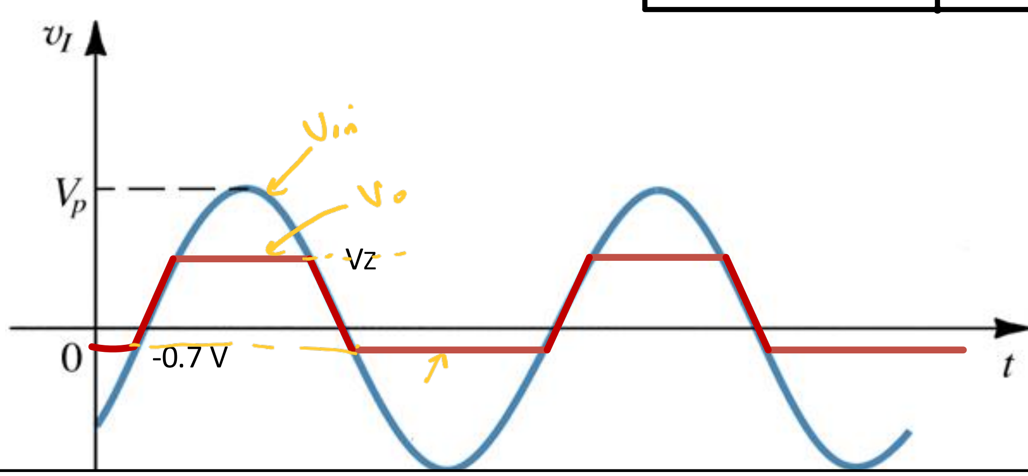
$$\therefore V_O(t) = V_Z$$

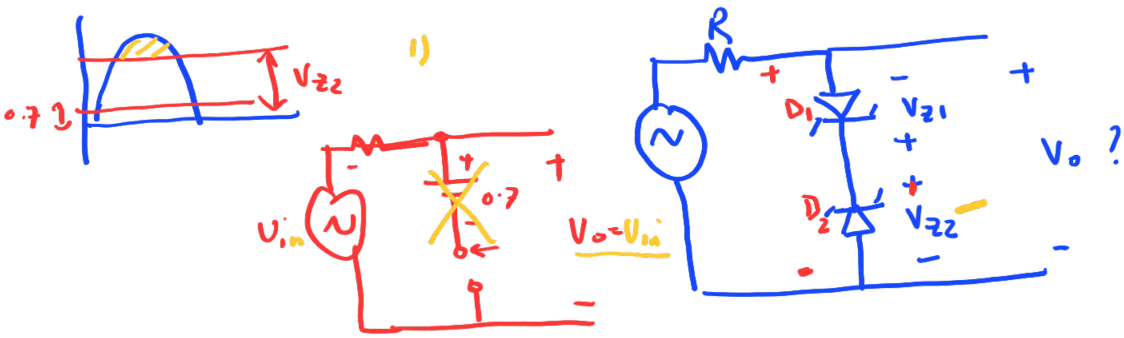
Clipper circuits using Zeners

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

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

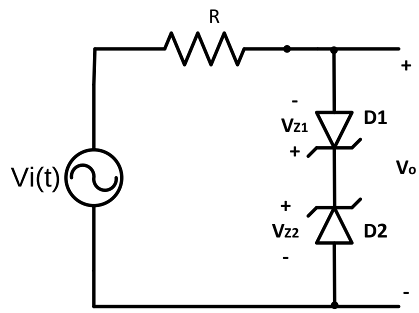






Clipper circuits using Zeners

Find and sketch $V_o(t)$

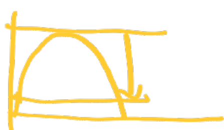


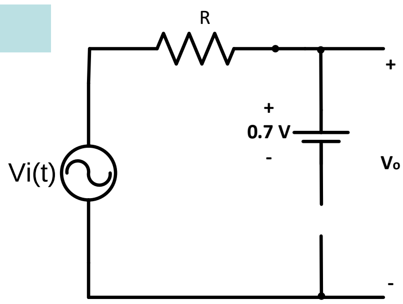
a) When 0.7V < $V_i(t)$ < V_{Z2},

D1- regular diode ON (1)

D2- regular diode OFF (2)

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



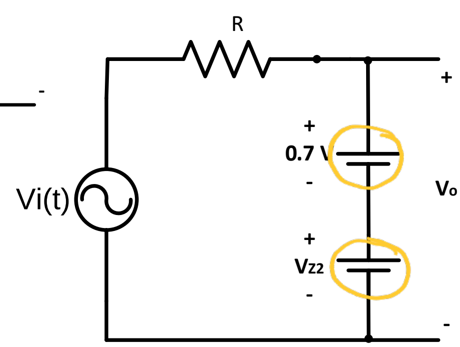


b) When $V_i(t) > V_{Z2}$

D1 – ON (region 1)

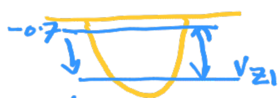
D2- Zener ON (region 3)

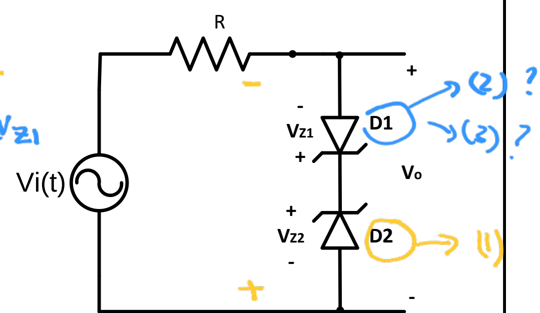
$$\therefore V_O(t) = \boxed{V_{Z2} + 0.7}$$



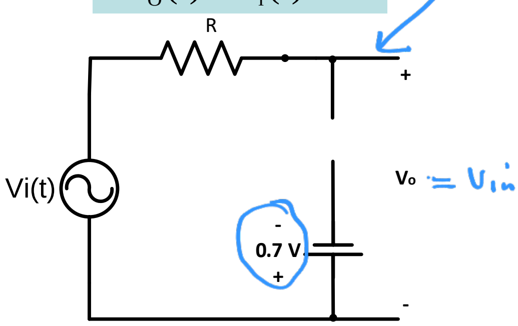
Clipper circuits using Zeners

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



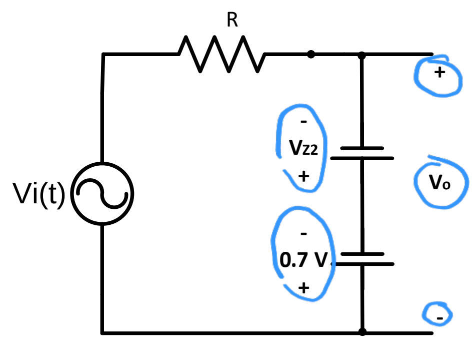


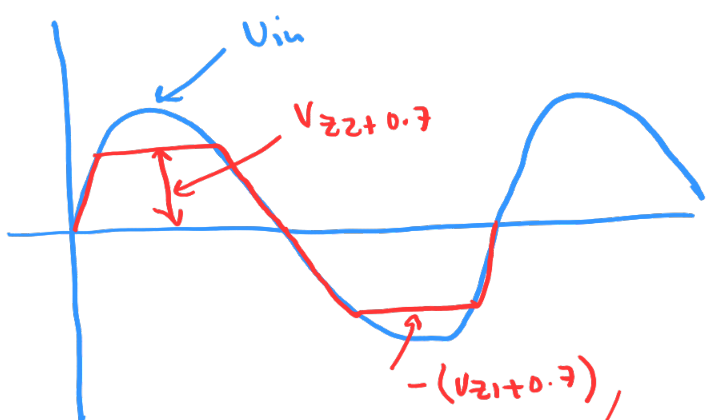
$$\therefore V_O(t) = V_i(t)$$

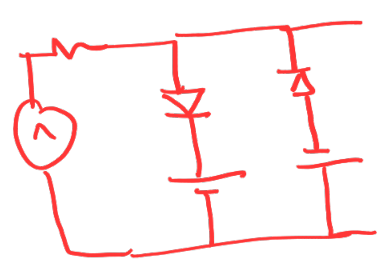


d) When $V_i(t) < -V_{Z1}$
D2 – ON (region 1)
D1- Zener ON (region 3)

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







similar to this circuit

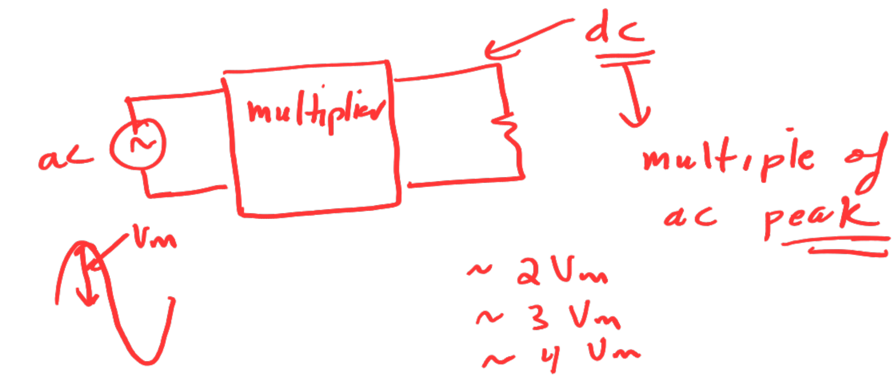
Voltage-Multiplier Circuits

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:

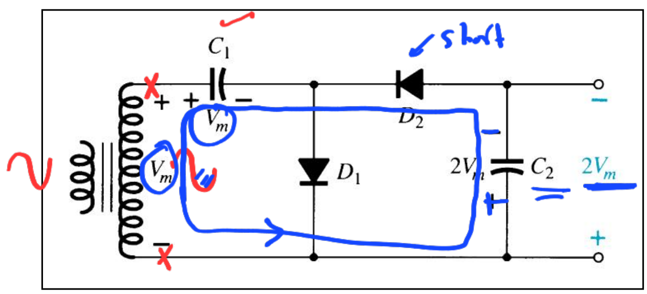
Voltage Doubler → x 2

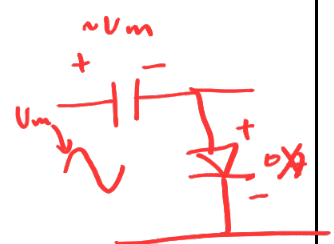
Voltage Tripler → x 3

Voltage Quadrupler → x 4



Voltage Doubler





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

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

where V_m = peak secondary voltage of the transformer

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Voltage Doubler

similar to clamper circuit

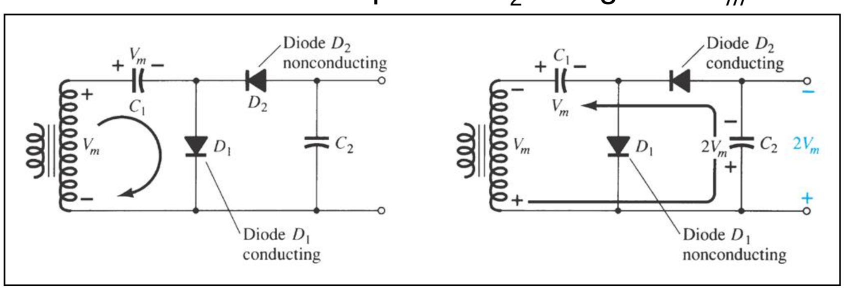
Positive Half-Cycle

D_1 conducts
D_2 is switched off
Capacitor C_1 charges to V_m

Negative Half-Cycle

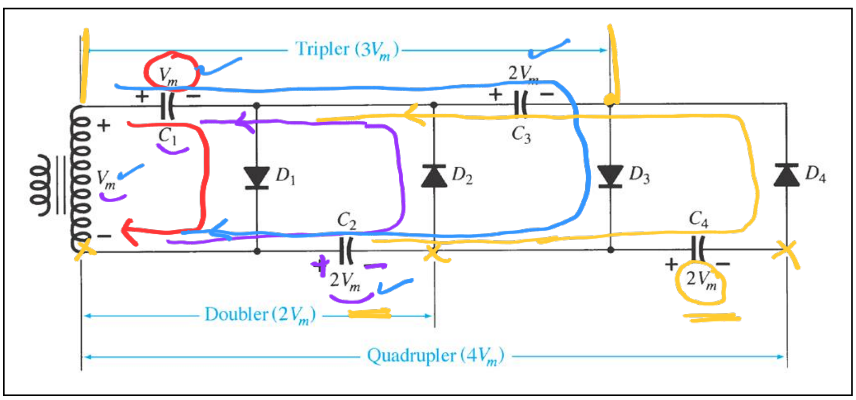
D_1 is switched off
D_2 conducts
Capacitor C_2 charges to V_m

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



Test in the Lab
ENEE2103

Voltage Tripler and Quadrupler



End of Diodes