ENEE236 & 241

Analog Electronics

L6 Diode Applications 4

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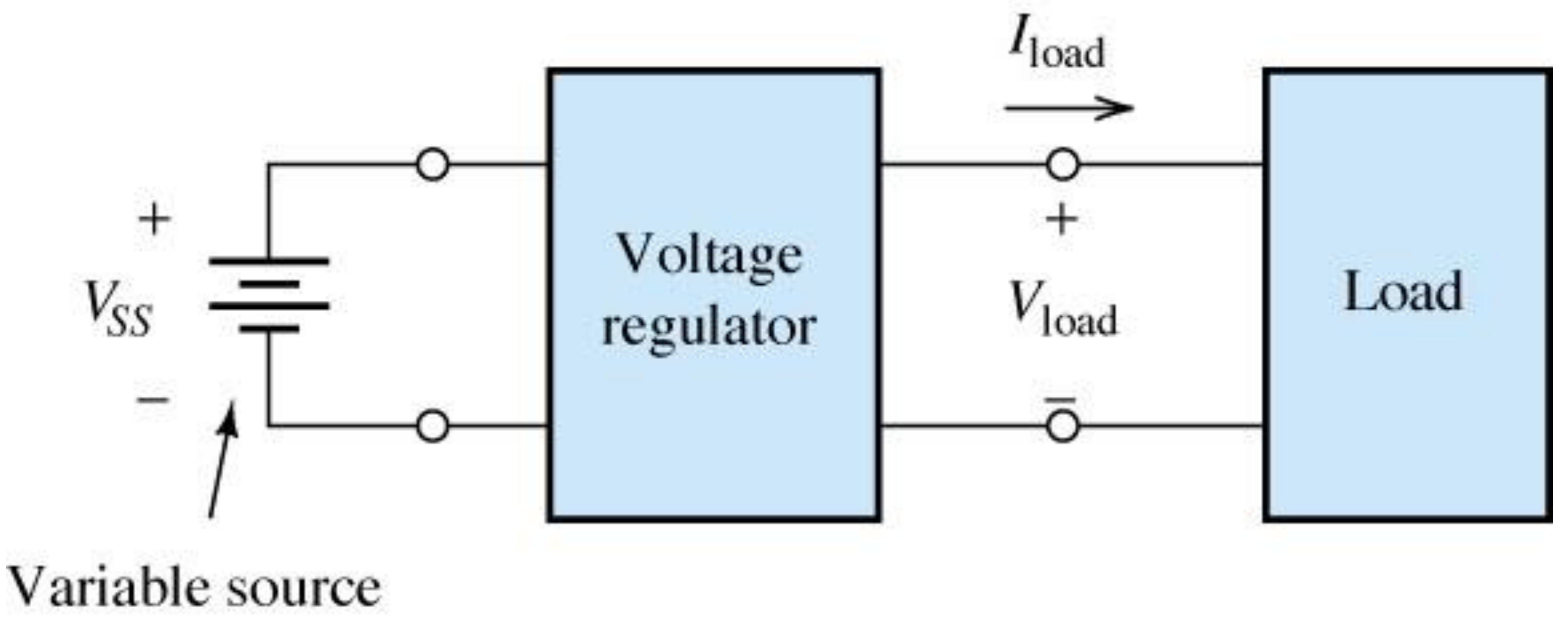
Zener Diode
Simple Voltage Regulator

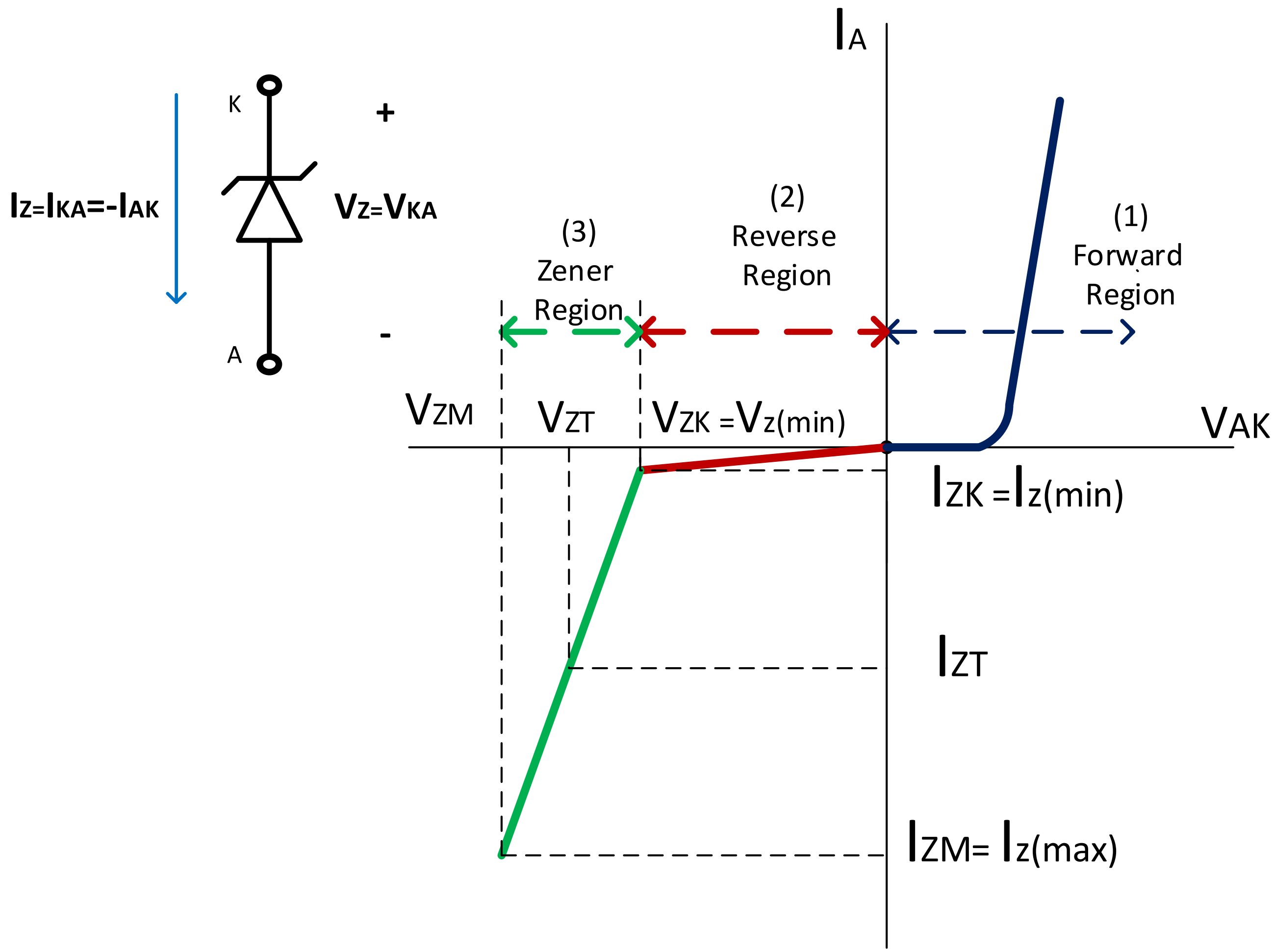
- *The Zener is used as a voltage regulator to maintain a constant dc output under variations in load current and ac line voltage*
- *It can also be used as protection device against overvoltage*
- *Analysis starts by defining state of diode followed by using appropriate model, then find unknown quantities*

Voltage Regulator



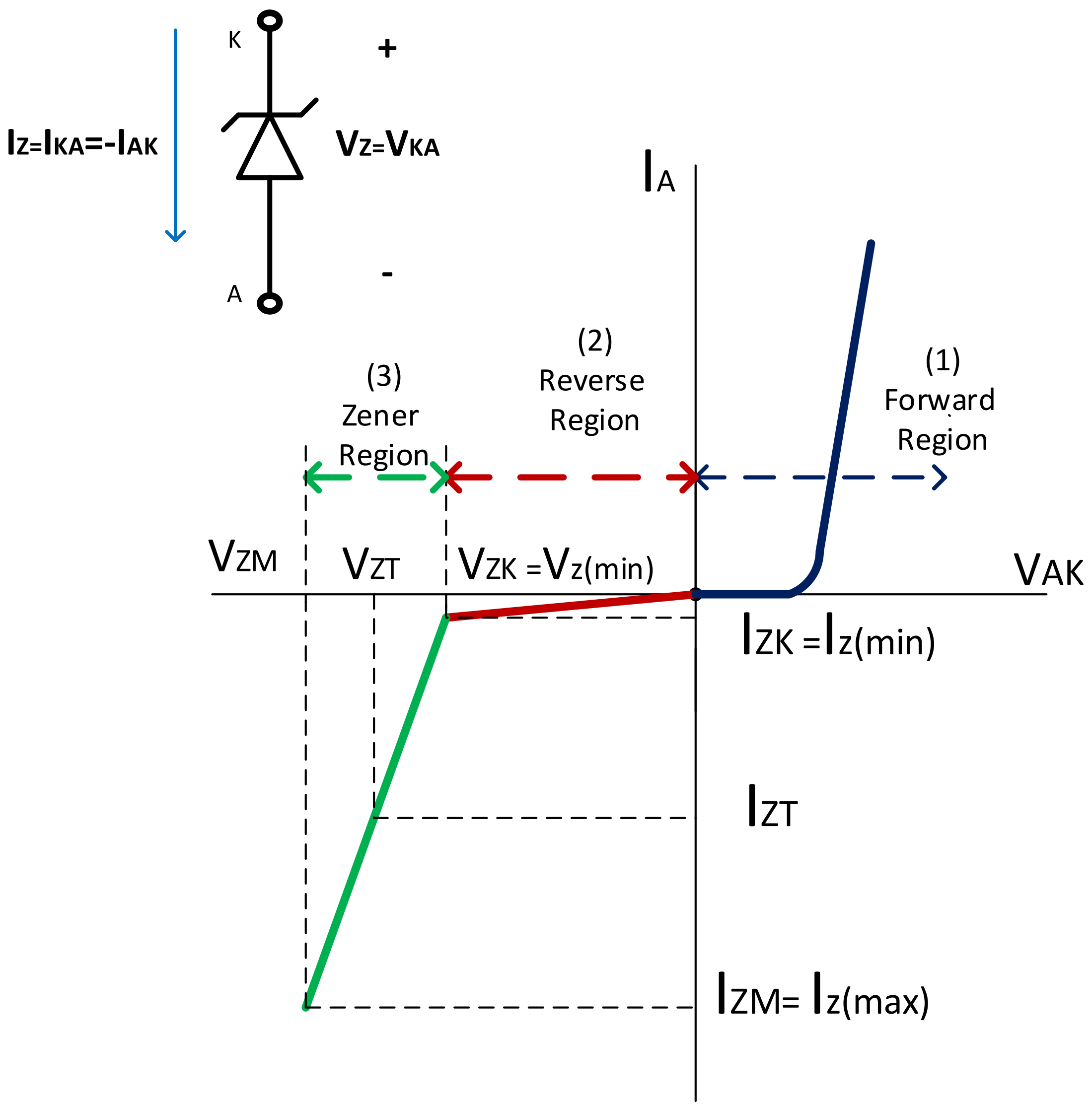
A voltage regulator supplies constant voltage to a load.

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 $V_{ZK}<V_{AK}<0$, zener acts as regular diode OFF

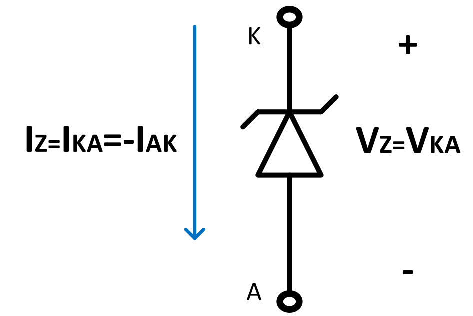
- Region (3)

When $V_{ZK}>V_{AK}$,
This is the intended operating region ,and the zener acts as a voltage regulator

- And $V_Z=V_{KA}$,it can be replaced by either a battery or a battery in series with resistor rZ

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

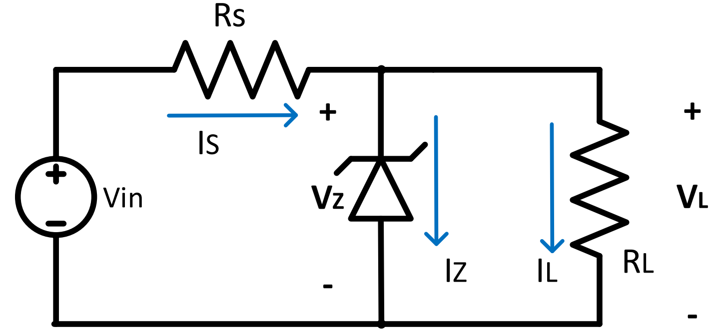
2. $V_{th} \geq V_Z$

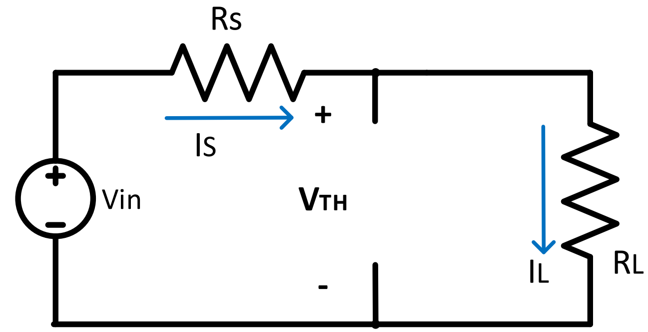
3. Iz > Iz(min)

4. Iz< Iz(max)

==> Voltage across the Zener is V_Z

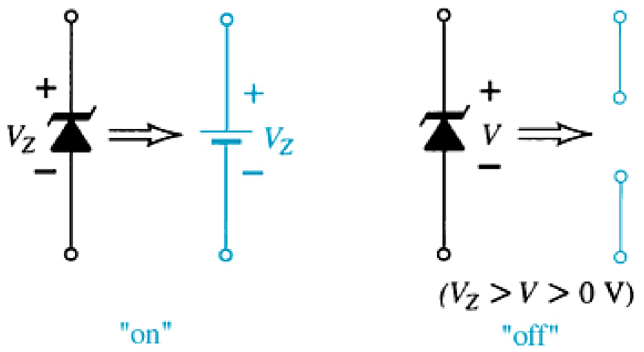
- Zener current: $I_Z = I_S - I_L$
- The Zener Power: $P_Z = V_Z I_Z$



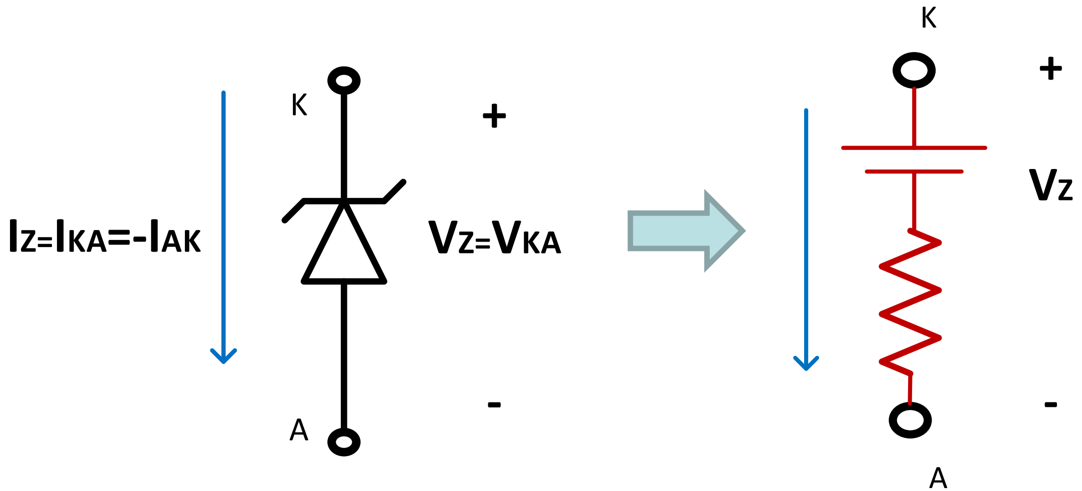


Zener Diode Models

1. Ideal Model



2. Simplified Model



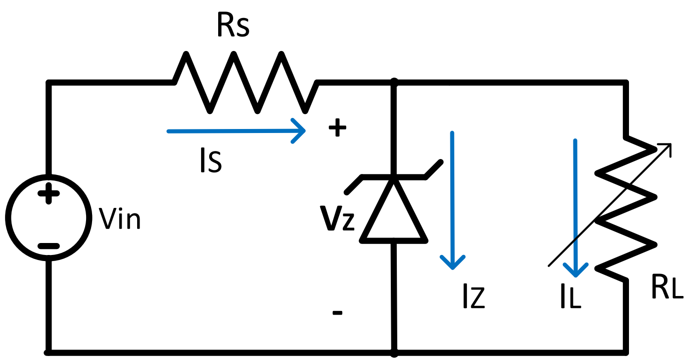
Fixed Vi, Variable RL

- *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 $\Rightarrow I_Z > I_{Z(\max)}$

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

$$\Downarrow$$

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

Example

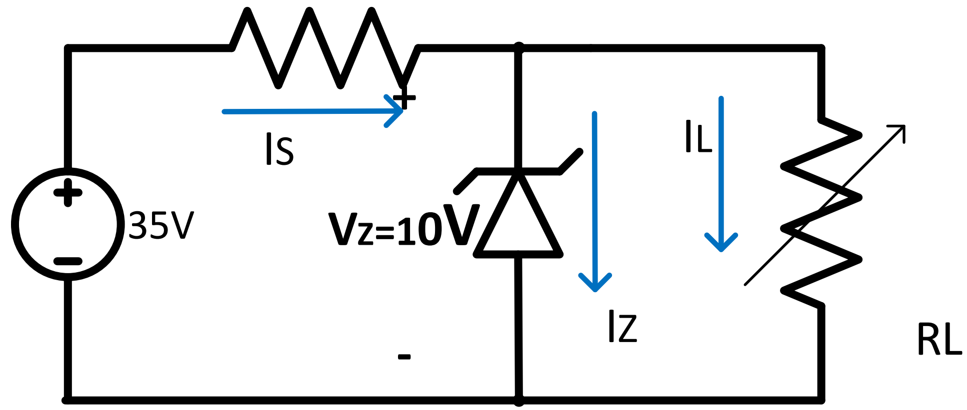
Given the following values of R_L, find the mode of operation of the zener and the voltage V_L

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) $R_L = 0.1\ k\Omega$

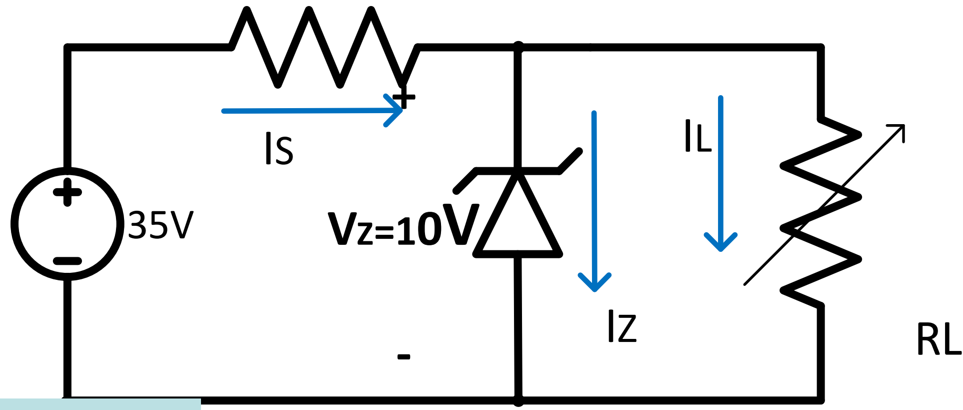
using ideal model

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

Zener works in region 2, it acts as open circuit

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

Example



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

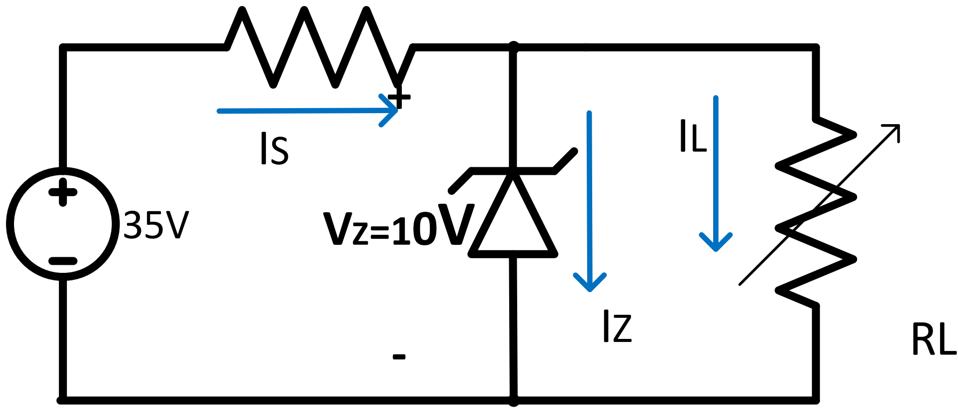
$$V_L = V_Z = 10\,V$$

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

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

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

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

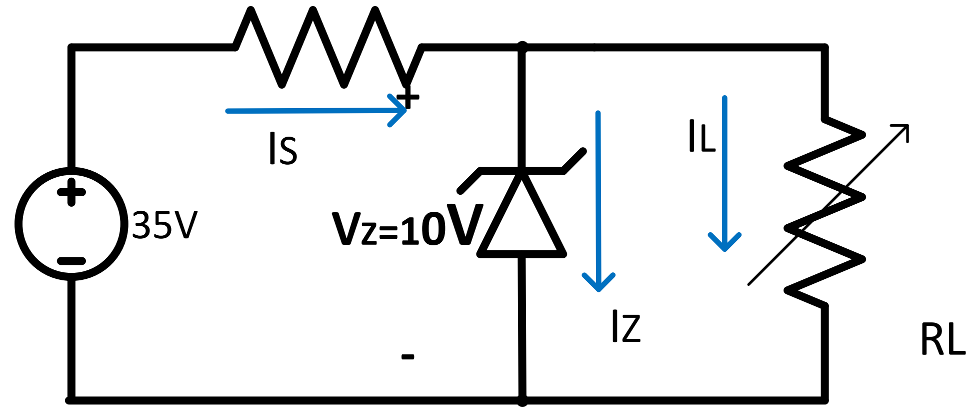
$$V_L = V_Z = 10\,V$$

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

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

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

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

$$V_L = V_Z = 10\ V$$

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

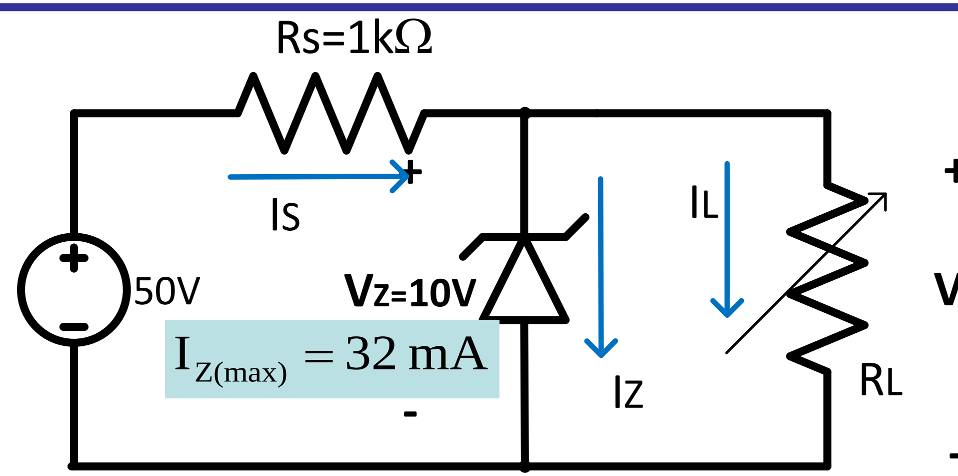
$$I_L = \frac{V_L}{R_L} = \frac{10}{\infty} = 0$$

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

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 $\ge P_{Z(max)}$

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 $I_{Z(\max)}$

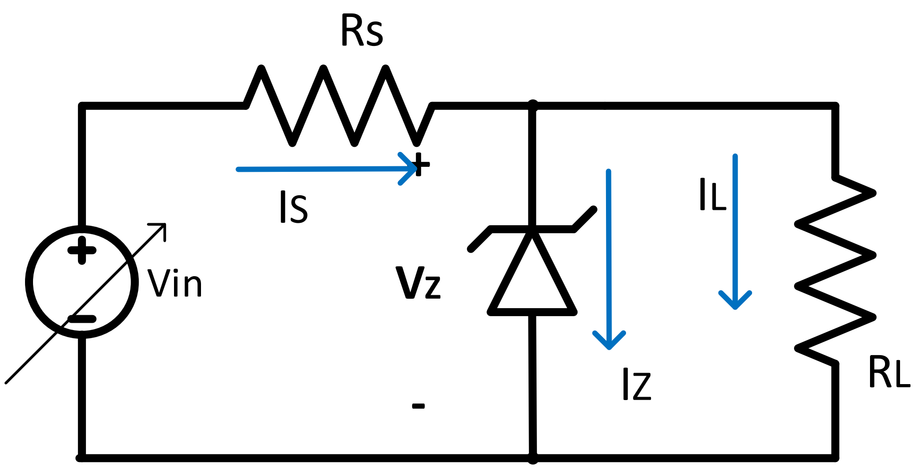
$$I_S = I_Z + I_L$$

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

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

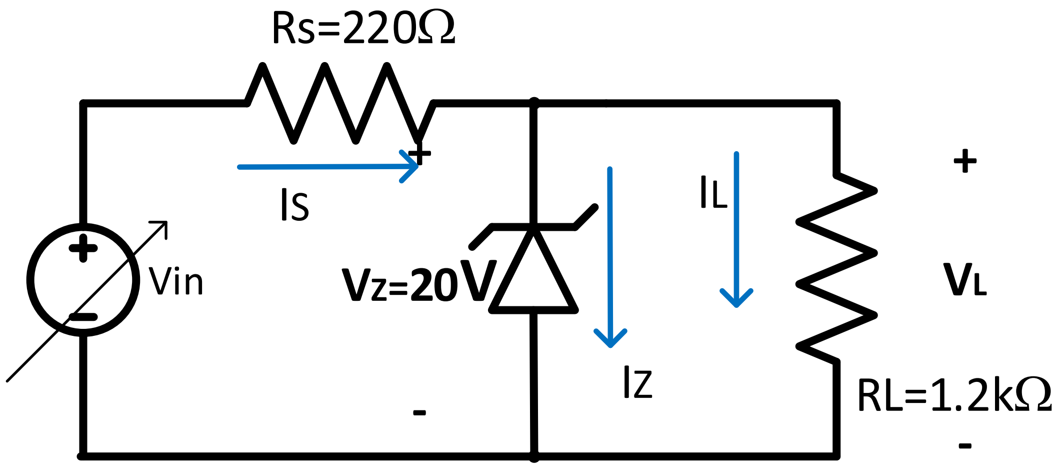
$$\Downarrow$$

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



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

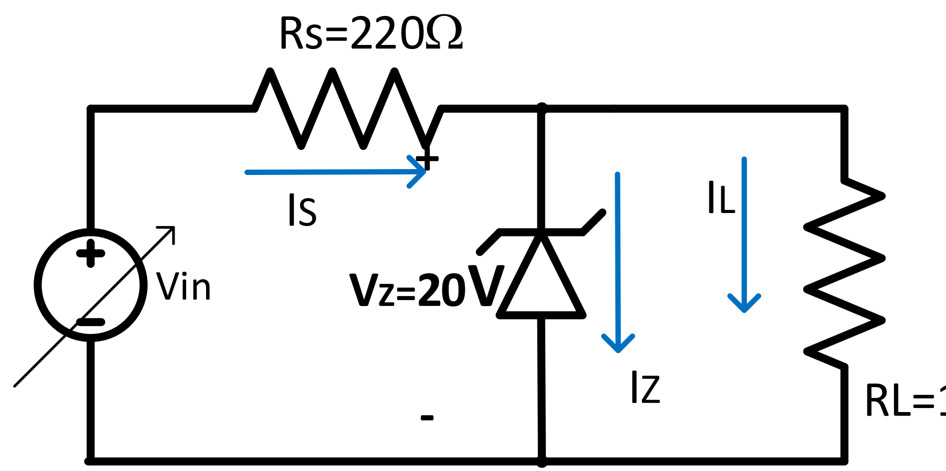
Find range of acceptable Rs in the voltage regulator

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

Worst Case : eht 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 :

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

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

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

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

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

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

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

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

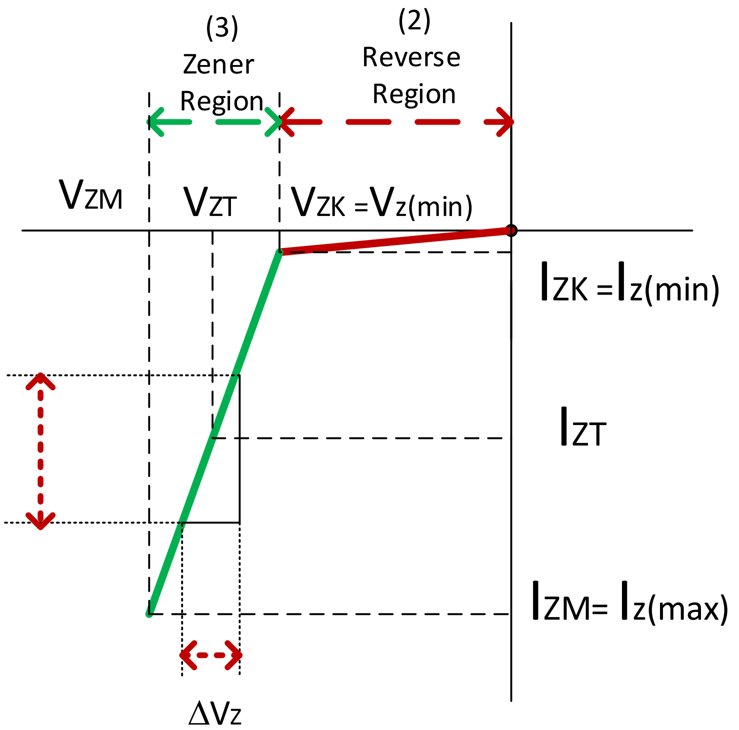
let $R_S = 100\ \Omega$

Variation of Vz (using simplified model)

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

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

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



Example

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

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

$I_{ZK} = 0.25\,\text{mA}$

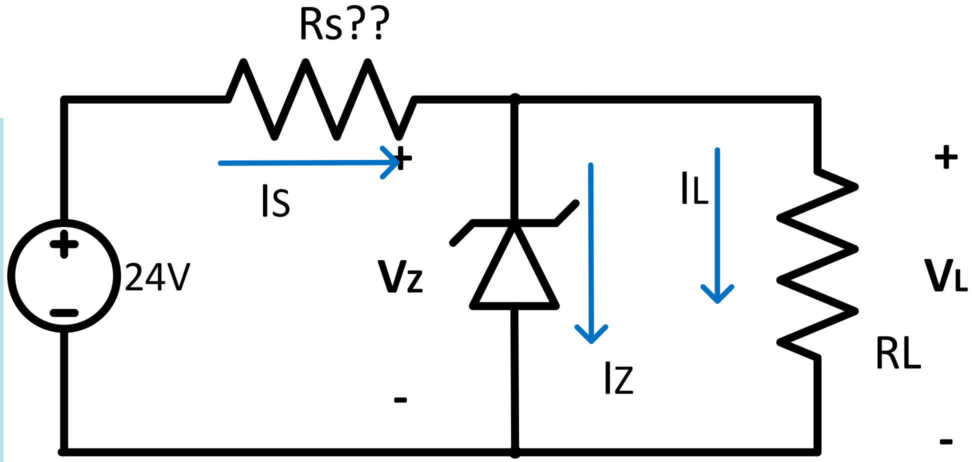
$P_{Zmax} = 1\,\text{Watt}$

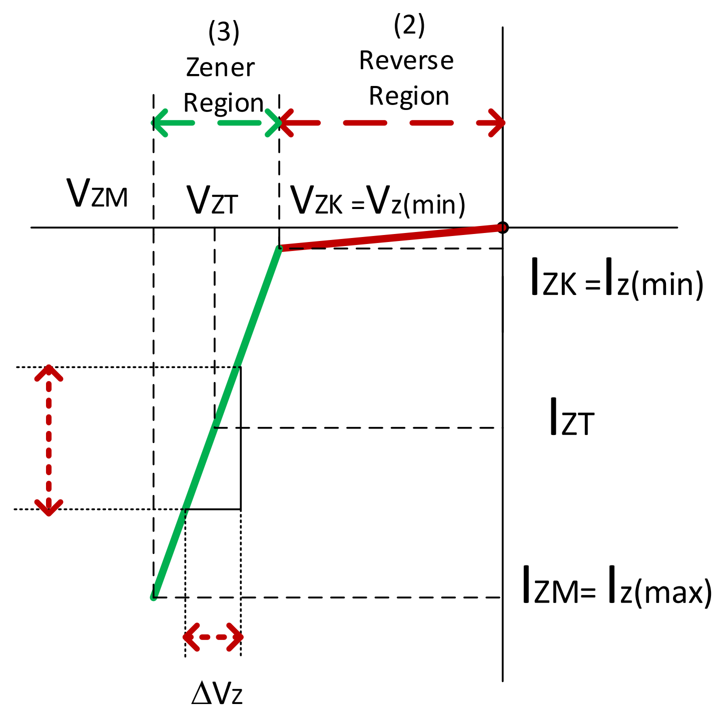
Find :

1)Minimum and Maximum Values of Vz

2)Value of R_S

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





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

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

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

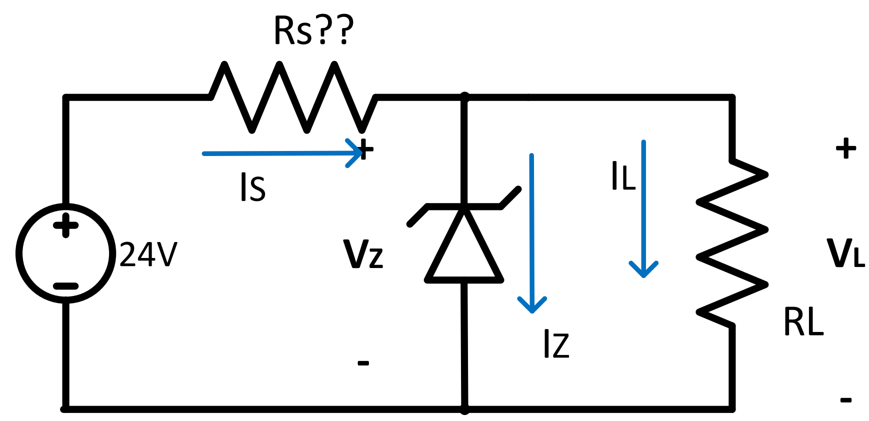
$= 15 + (66.7 - 17)\,\text{mA}\,(14\,\Omega) = 15.7\ \text{V}$

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

$= V - (I - I) \,.\, r$

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

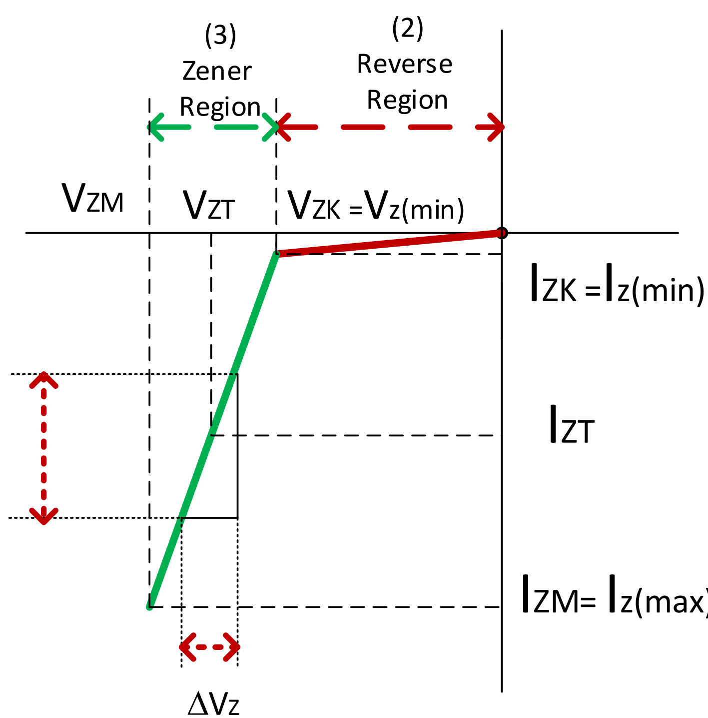
$$\frac{V_{S(min)} - V_Z}{I_{Z(min)} + I_{L(max)}} \geq R_S \geq \frac{V_{S(max)} - V_Z}{I_{Z(max)} + I_{L(min)}}$$

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

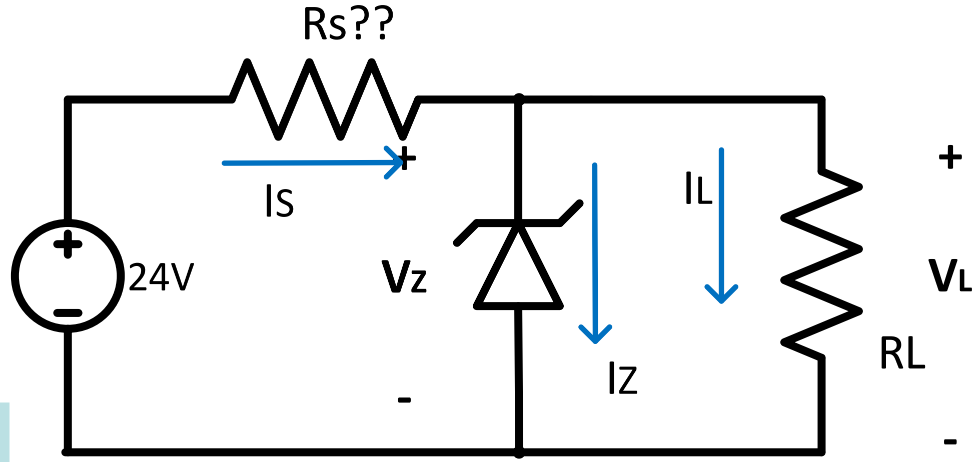
$$R_S \geq \frac{V_S - V_{Z(max)}}{I_{Z(max)} + I_{L(min)}} = \frac{24 - 15.7}{66.7\ mA + 0} = 124\,\Omega$$

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

we choose $R_S = 124\Omega$



Example

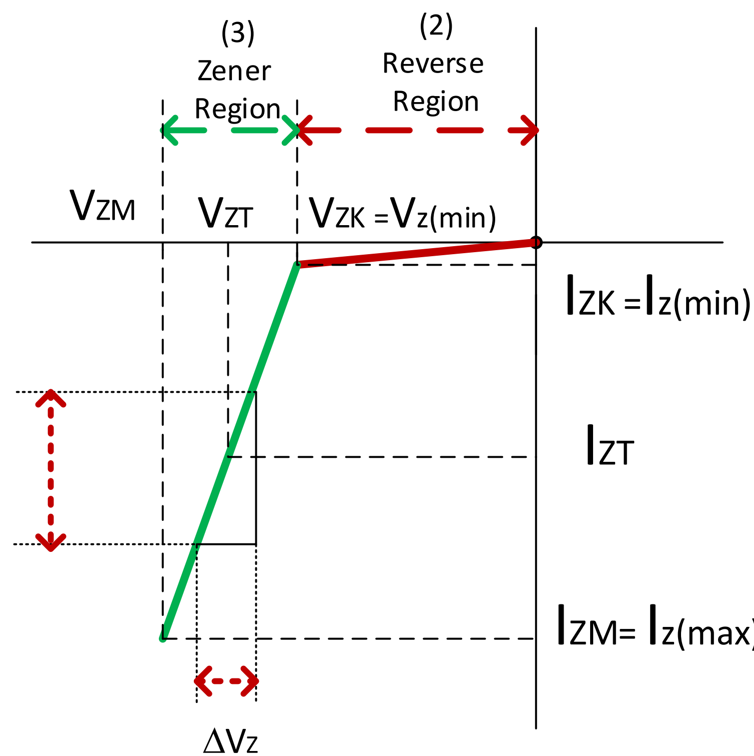


$$3)R_{L(min)} \Rightarrow I_{L(max)}$$

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

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

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



Clipper circuits using Zeners

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

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

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

$$V_i(t) < -0.7$$

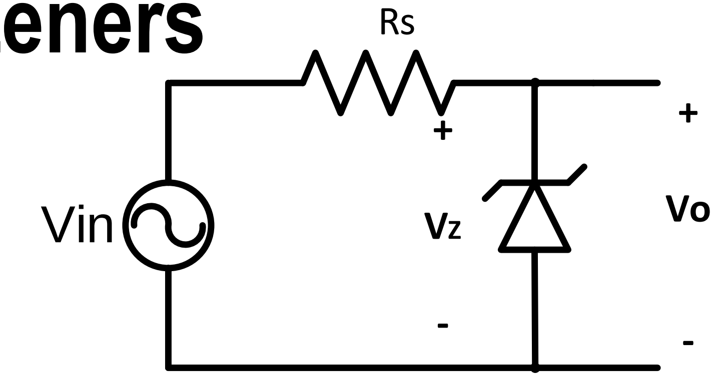
$$\therefore V_O(t) = -0.7$$

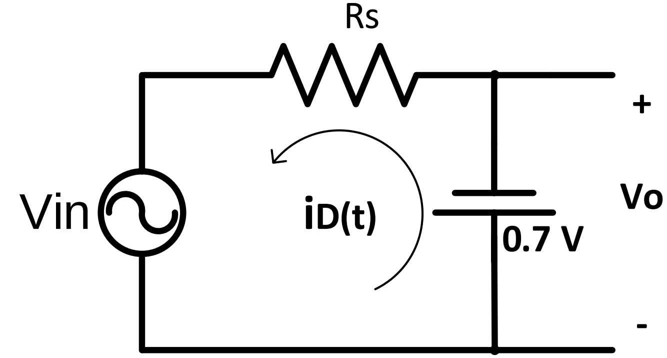
b) When $V_Z > V_i(t) > -0.7$ V, Zener works in region (2) as regular diode OFF

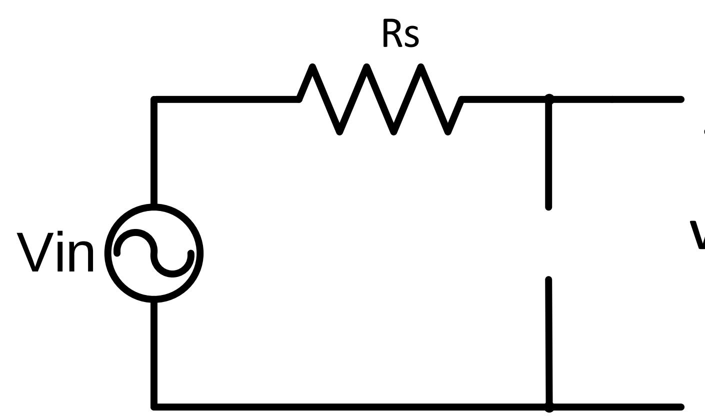
$$\therefore V_O(t) = V_i(t)$$

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

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



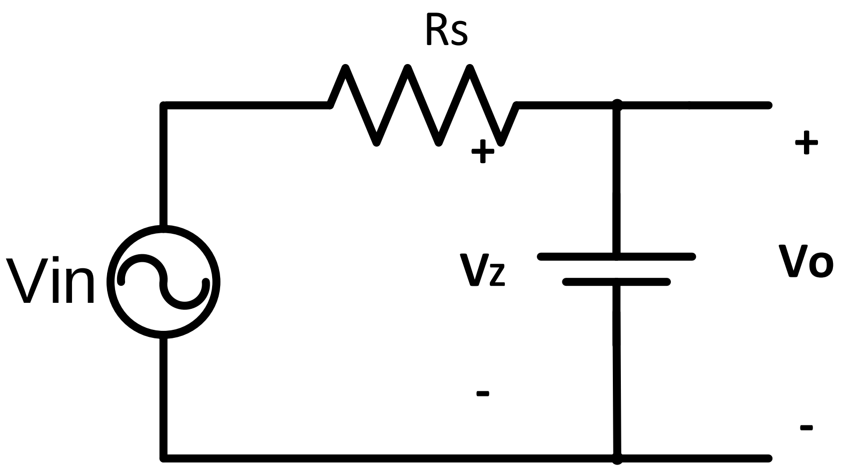


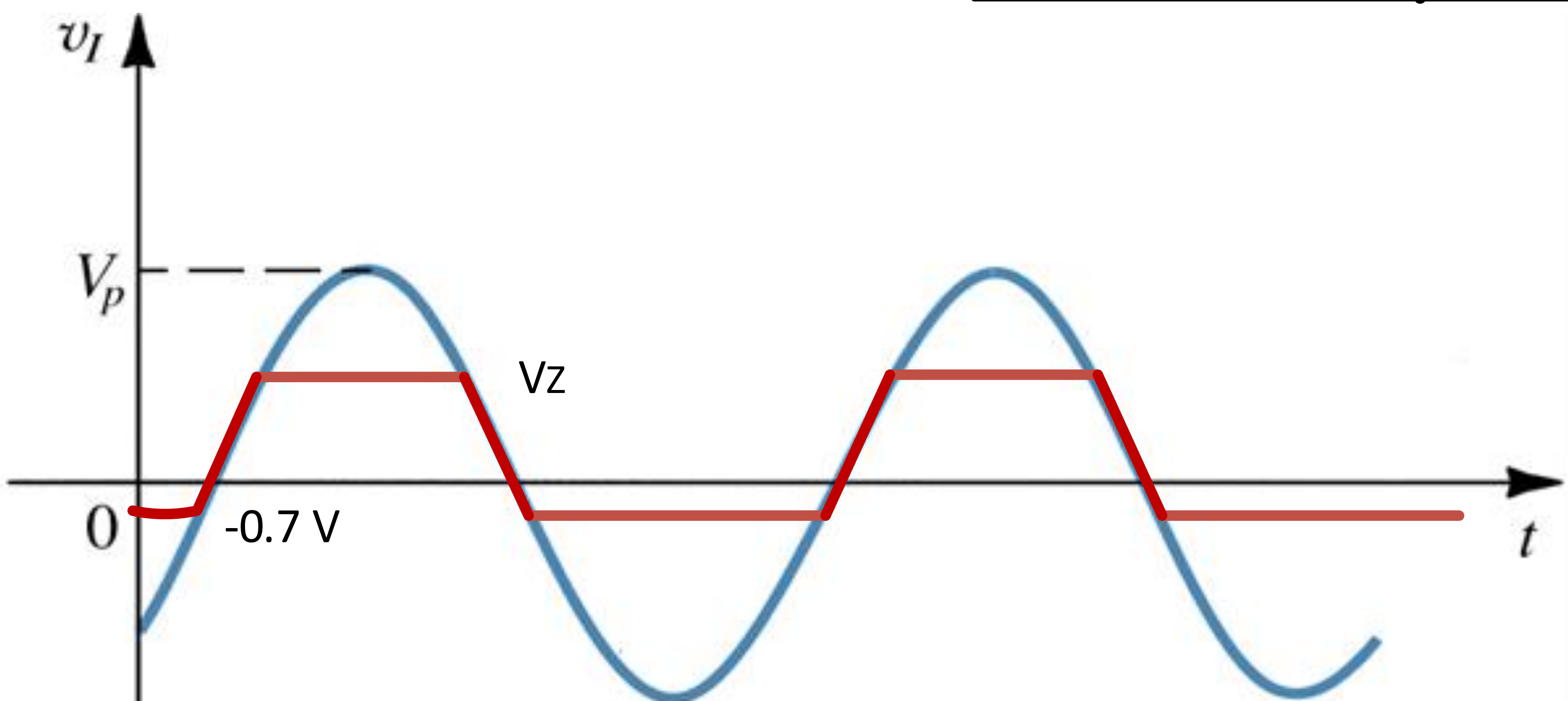


Clipper circuits using Zeners

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

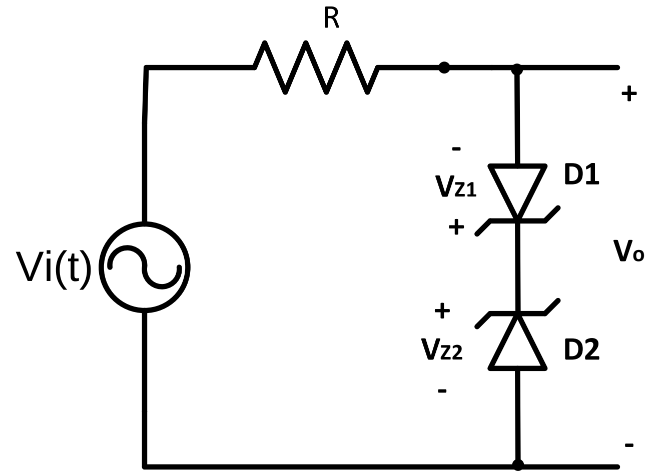
$$\therefore V_O(t) = V_Z$$





Clipper circuits using Zeners

Find and sketch $V_o(t)$

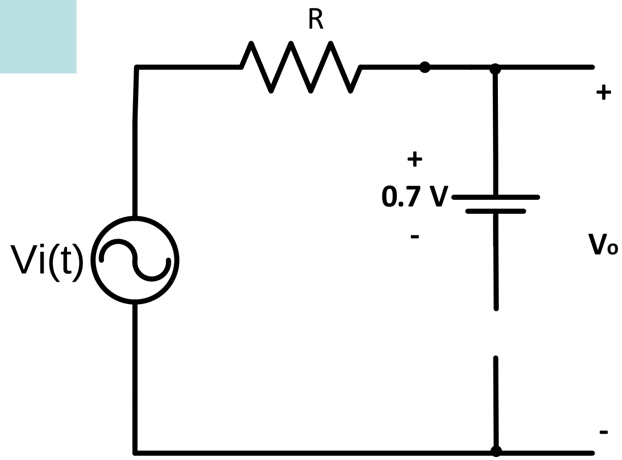


a) When $0.7V < V_i(t) < V_{Z2}$,

D1- regular diode ON

D2- regular diode OFF

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

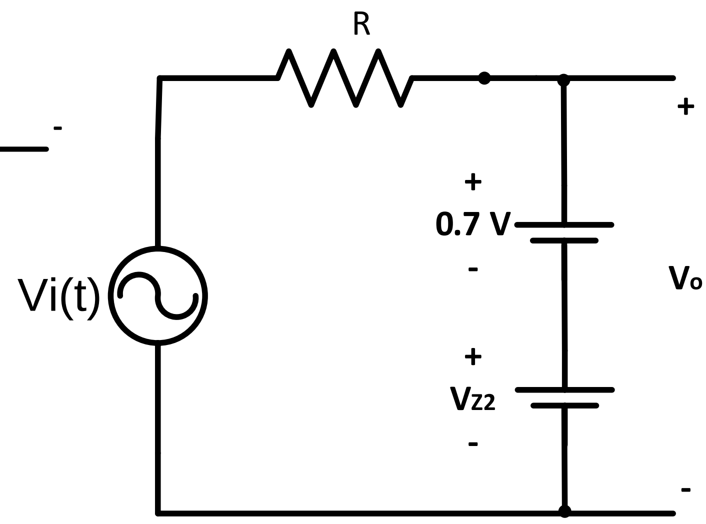


b) When $V_i(t) > V_{Z2}$

D1 – ON (region 1)

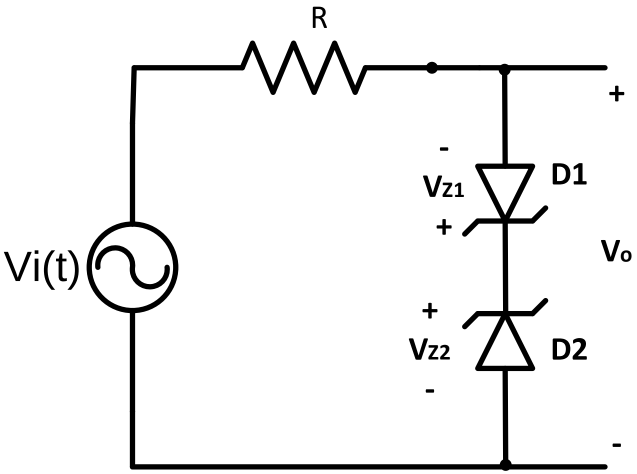
D2- Zener ON (region 3)

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

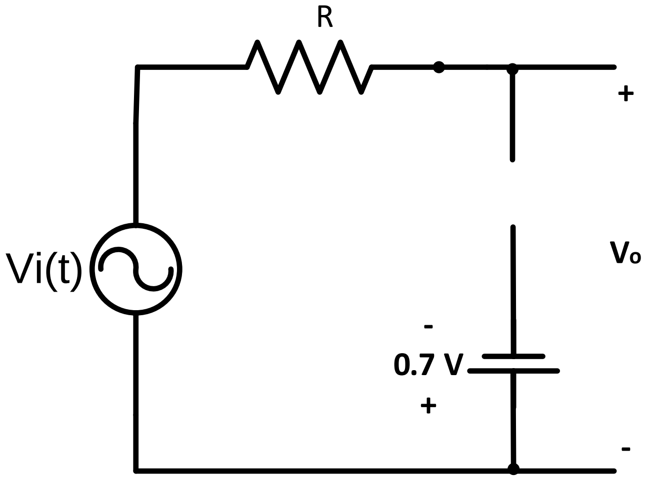


Clipper circuits using Zeners

c) When -0.7V >Vi(t) > -VZ1,
D1- regular diode OFF
D2- regular diode ON

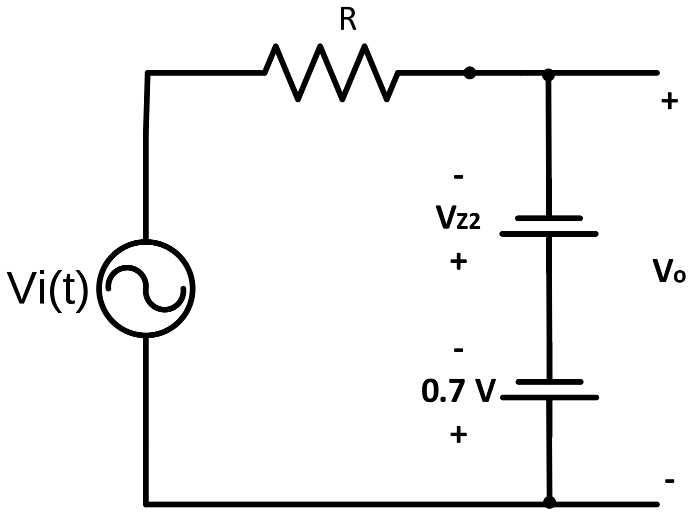


$$\therefore V_O(t) = V_i(t)$$

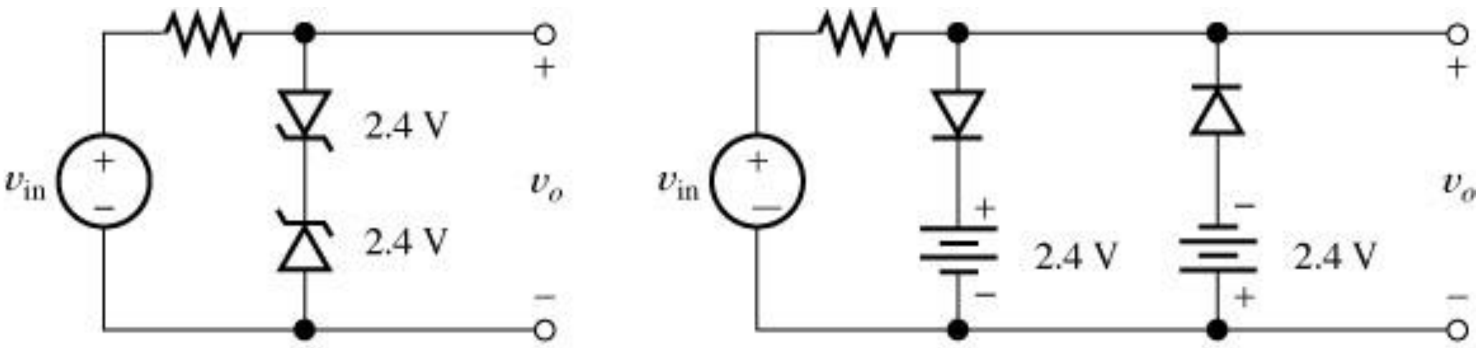


d) When Vi(t) < -VZ1
D2 – ON (region 1)
D1- Zener ON (region 3)

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



Clipper circuits using zeners



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

Voltage-Multiplier Circuits

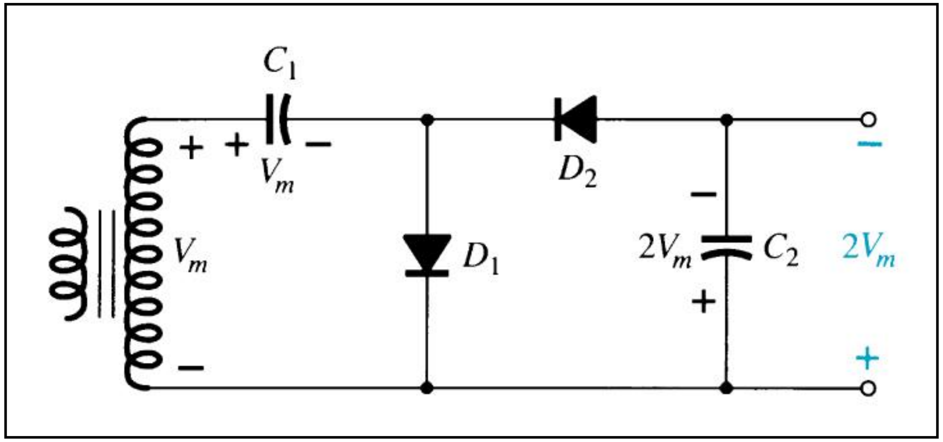
Voltage multiplier circuits use a combination of diodes and capacitors to step up the output voltage of rectifier circuits. Three common voltage multipliers are the:

Voltage Doubler

Voltage Tripler

Voltage Quadrupler

Voltage Doubler



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

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

where V_m = peak secondary voltage of the transformer

Voltage Doubler

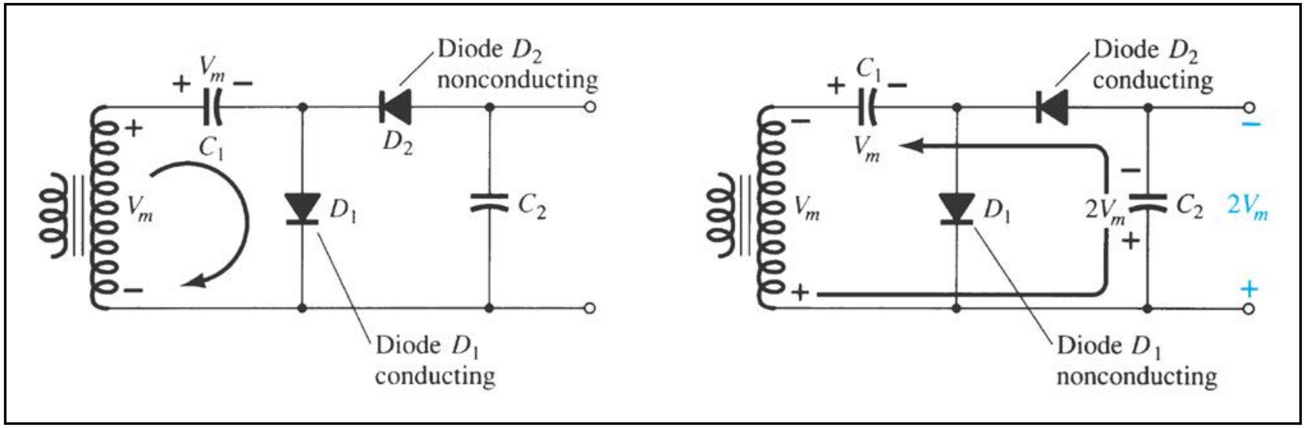
Positive Half-Cycle

D_1 conducts
D_2 is switched off
Capacitor C_1 charges to V_m

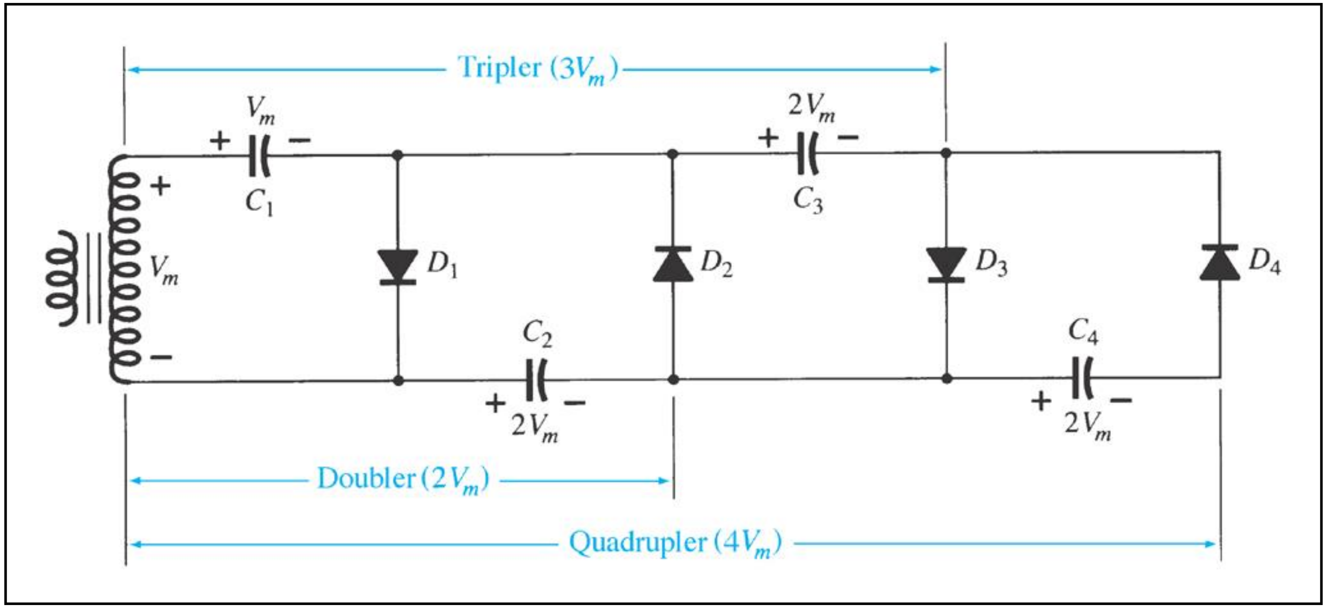
Negative Half-Cycle

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



Practical Applications

Rectifier Circuits

Conversions of AC to DC for DC operated circuits
Battery Charging Circuits

Simple Diode Circuits

Protective Circuits against
Overcurrent
Polarity Reversal
Currents caused by an inductive kick in a relay circuit

Zener Circuits

Overvoltage Protection
Setting Reference Voltages