Lecture 7 :
Zener Diodes

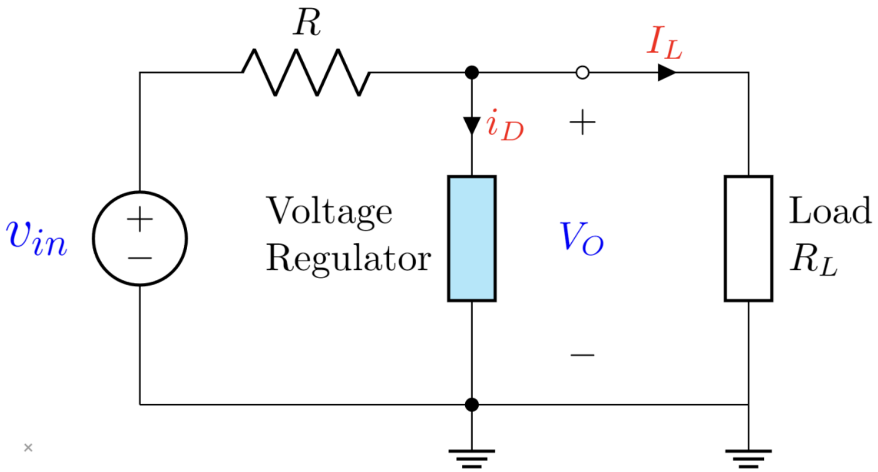
Outline

- Voltage Regulators
- Forward Bias (FB) Diodes as Voltage Regulators
- Drawbacks of (FB) Diodes as Voltage Regulators
- Diode Breakdown Region
- Zener Diodes – Introduction and analysis
- Zener Diodes as Voltage Regulators
- Practice Problems

Voltage Regulators

- **Voltage Regulation** is the measure of how well a system can provide near *constant voltage*.

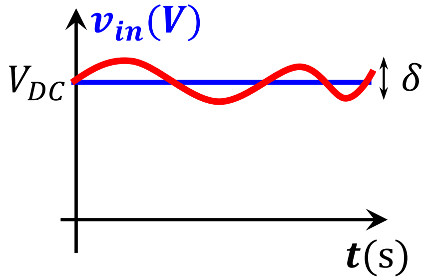
- **Voltage Regulators** provide steady voltage independent of how much power is drawn from the power source

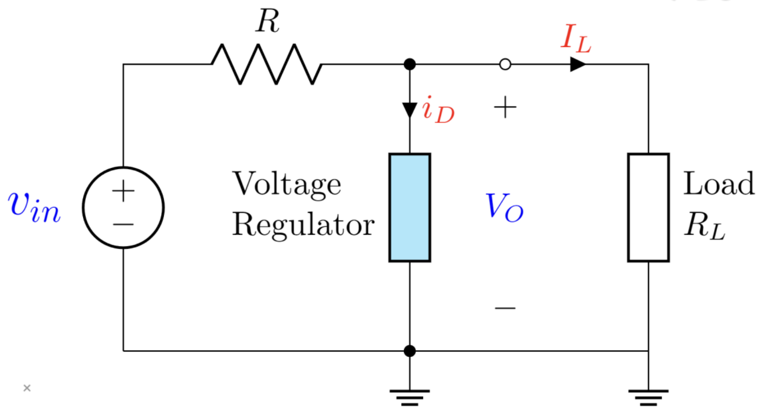


Voltage Regulator:
Tries to maintain a voltage constant at V_O

Voltage Regulators

Let's assume that v_{in} is not a perfect DC source. It supplies a voltage of $(V_{DC} \pm \delta)$ V





Voltage Regulator:

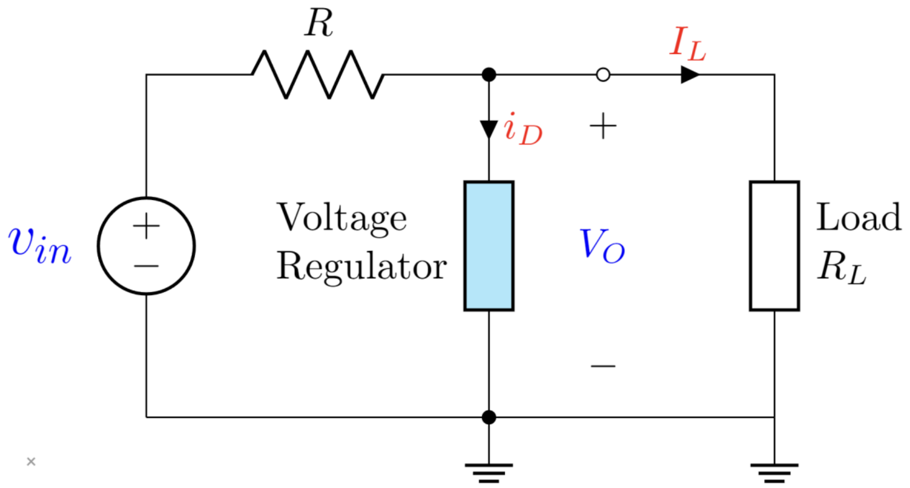
Tries to maintain a voltage constant at V_O **even when v_{in} is varying.**

Variables: V_O should remain constant irrespective of the changes in the following quantities:

1. **Input Voltage**: v_{in} 2. **Load Current: I_L** 3. **VR current: i_D**

Voltage Regulator – Worst Case Scenario

Worst Case Scenario occurs when the three variables (v_{in}, I_L, and i_D) change in such a way, such that maintaining V_O constant requires the most power (current) from the **Voltage Regulator.**



The **Voltage regulator** is at its maximum capacity at the worst case.

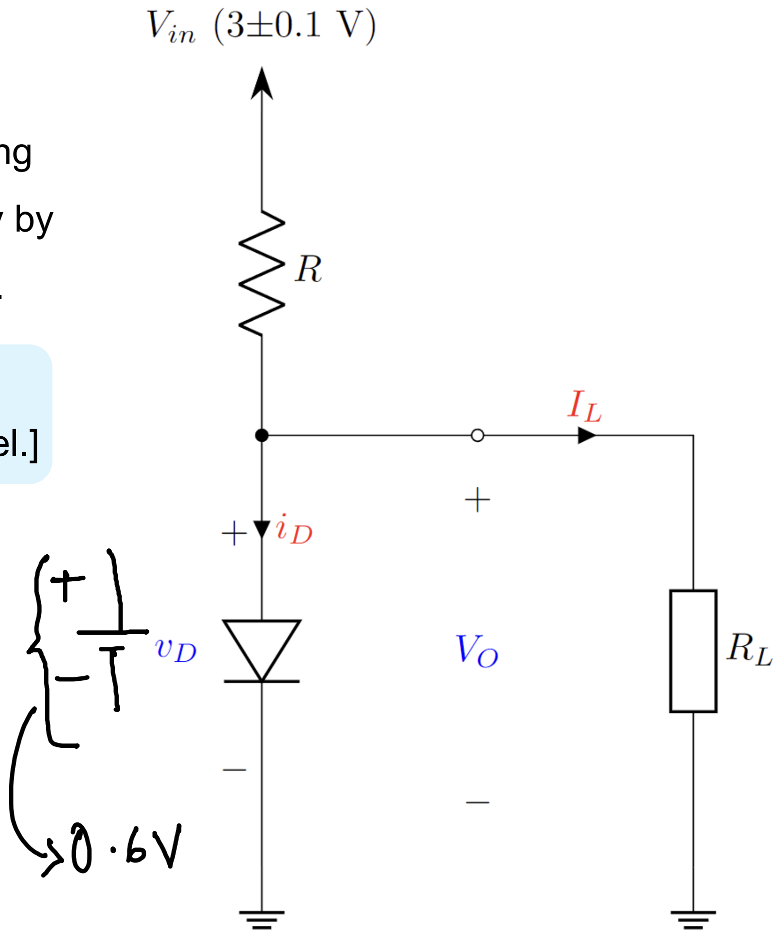
Worst Case Scenario occurs when

1. **Input Voltage is minimum:** $v_{in}(\text{min})$
2. **Load Current is maximum:** $I_L(\text{max})$
3. **VR current minimum:** $i_D(\text{min})$

Practice Problem 1

The circuit of the adjacent **Figure** is specified to have the following parameters. The supply voltage $\boldsymbol{V_{in}}$ is nominally $\mathbf{3}$ V but can vary by $\pm\,\mathbf{0.1}\ \boldsymbol{V}$. $\boldsymbol{R_L}$ can draw a maximum of $\mathbf{10}$ mA and $\boldsymbol{i_D}(\min) = \mathbf{1}$ mA.

What is $\boldsymbol{R}$ for worst case scenario if $\boldsymbol{v_D}$ ($\boldsymbol{V_O}$) is to be regulated at $\mathbf{0.6}$ V? [Since r_o is not provided, you can consider the CVD model.]



Solution:

Worst Case Scenario occurs when

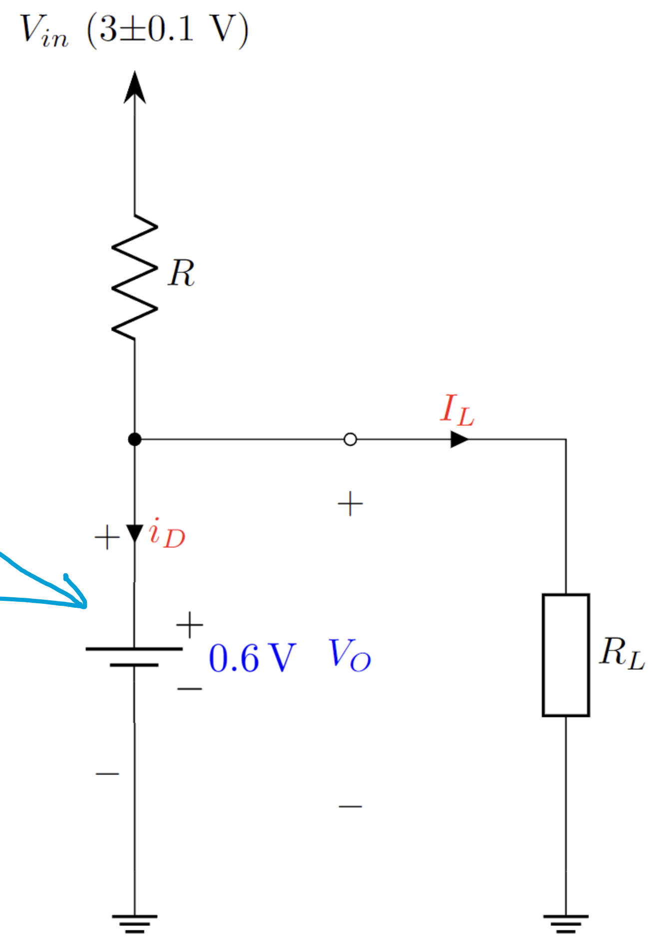
1. $v_{in}(\min) = 3 - 0.1\ \text{V} = 2.9\ \text{V}$
2. $I_L(\max) = 10\ \text{mA}$
3. $i_D(\min) = 1\ \text{mA}$

$$\frac{v_{in}(\min) - 0{\cdot}6}{R} = I_L(\max) + i_D(\min)$$

Practice Problem 1

The circuit of the adjacent **Figure** is specified to have the following parameters. The supply voltage $\boldsymbol{V_{in}}$ is nominally $\mathbf{3}$ V but can vary by $\pm\,\mathbf{0.1}\ \boldsymbol{V}$. $\boldsymbol{R_L}$ can draw a maximum of $\mathbf{10}$ mA and $\boldsymbol{i_D}(\min) = \mathbf{1}$ mA.

What is $\boldsymbol{R}$ for worst case scenario if $\boldsymbol{v_D}$ ($\boldsymbol{V_O}$) is to be regulated at $\mathbf{0.6}$ V? [Since r_o is not provided, you can consider the CVD model.]



Solution:

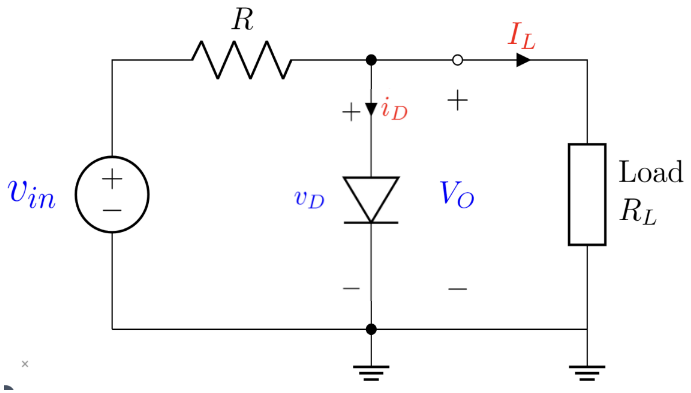
$$\frac{v_{in}(\min) - 0.6}{R} = I_L(\max) + i_D(\min)$$

$$R = \frac{2.9 - 0.6}{10 - 1}\ k\Omega = 0.209\ k\Omega$$

$$\therefore R = 209\ \Omega$$

Drawbacks of Diodes as Voltage Regulators

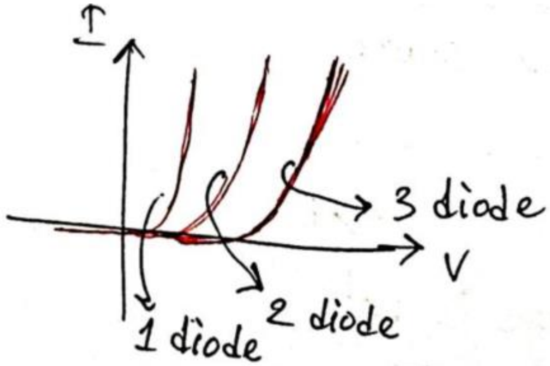
- **Regulation voltage is low:** $\sim \boldsymbol{V_{DO}}$ (0.3 ~1 V)
- **High** $\boldsymbol{i_D}$(min)
- $\boldsymbol{R}$ **can be low → High power loss**



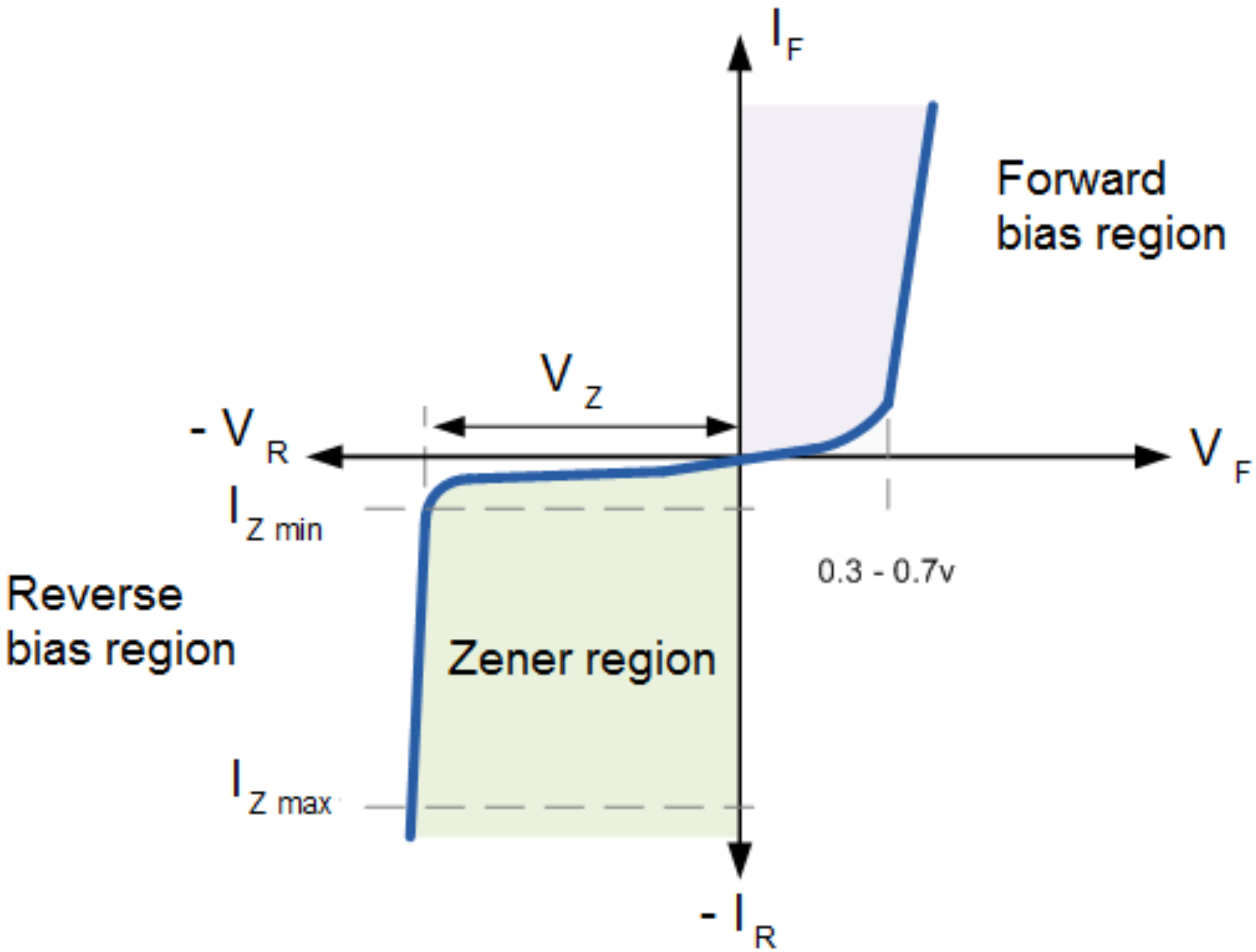
Possible Solution:

Stacked Diodes in Series: -- Regulation Voltage can be increased to $\boldsymbol{n \cdot V_{DO}}$ for $\boldsymbol{n}$ stacked diodes.

However, this can make the diodes deviate more from ideal model. **IV characteristics** become flatter (more lossy).



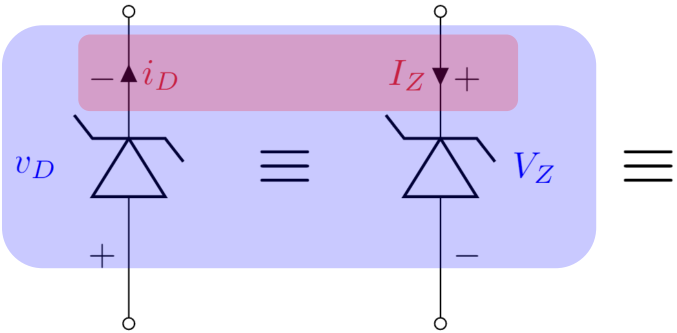
Zener Diode IV

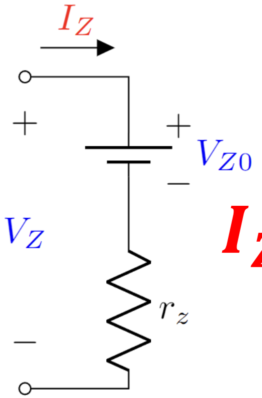


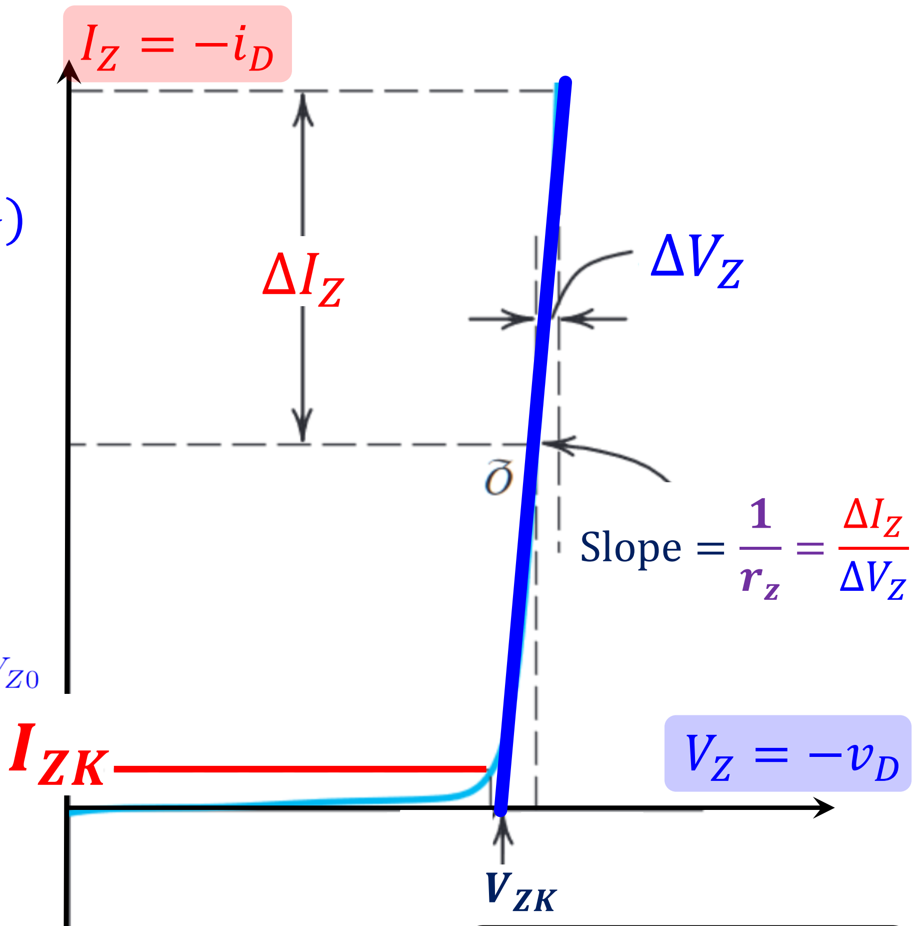
Zener Diode IV

Breakdown Region $(V_Z > V_{Z0} \approx V_{ZK})$

$$V_Z = V_{Z0} + I_Z r_z$$



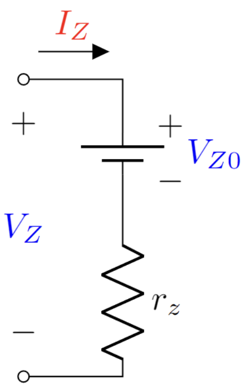




In this **Breakdown region**, the diode acts almost like a **"constant voltage source".**

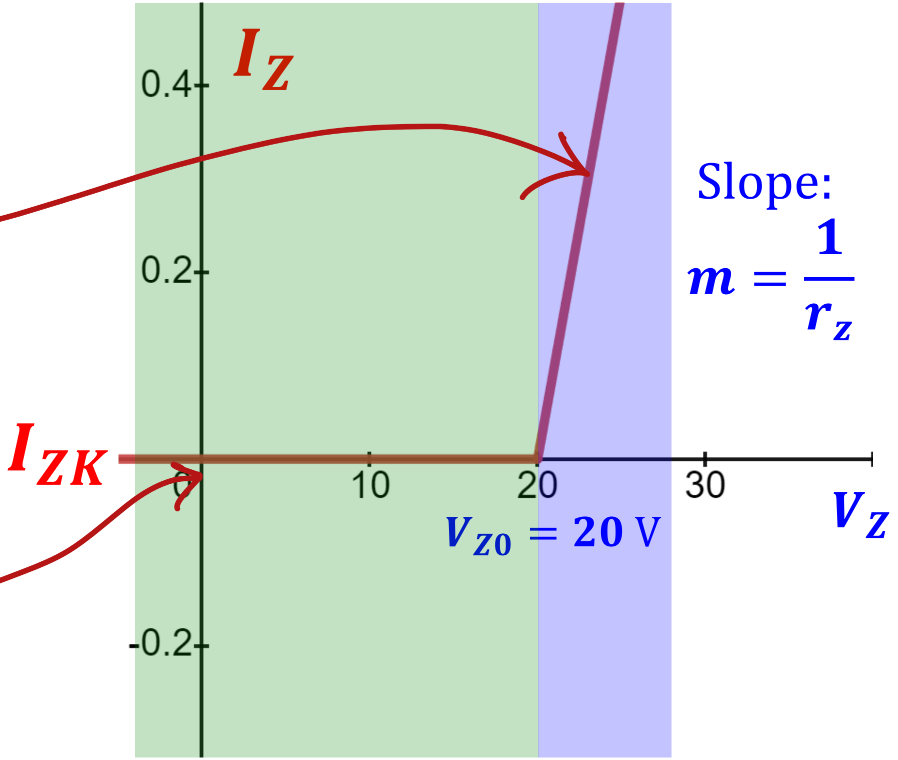
Zener Diode Breakdown IV Characteristic

Breakdown Region $(V_Z > V_{Z0} \approx V_{ZK})$



$$V_Z = V_{Z0} + I_Z r_Z$$

$$I_Z = I_{ZK}$$



V_Z: Total RB Voltage Across **Zener** diode

V_{Z0}: Zener knee voltage

Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10}\ \boldsymbol{V}$ but can vary by $\pm\mathbf{1}\ \boldsymbol{V}$.

$V^+ = 10 \pm 1\,V$

$V_Z = 6.8\,V$ at $I_Z = 5\,mA$

$r_z = 20\ \Omega.$

$I_{ZK} = 0.2\,mA.$

(a) Find V_0 with no load and with V^+ at its nominal value

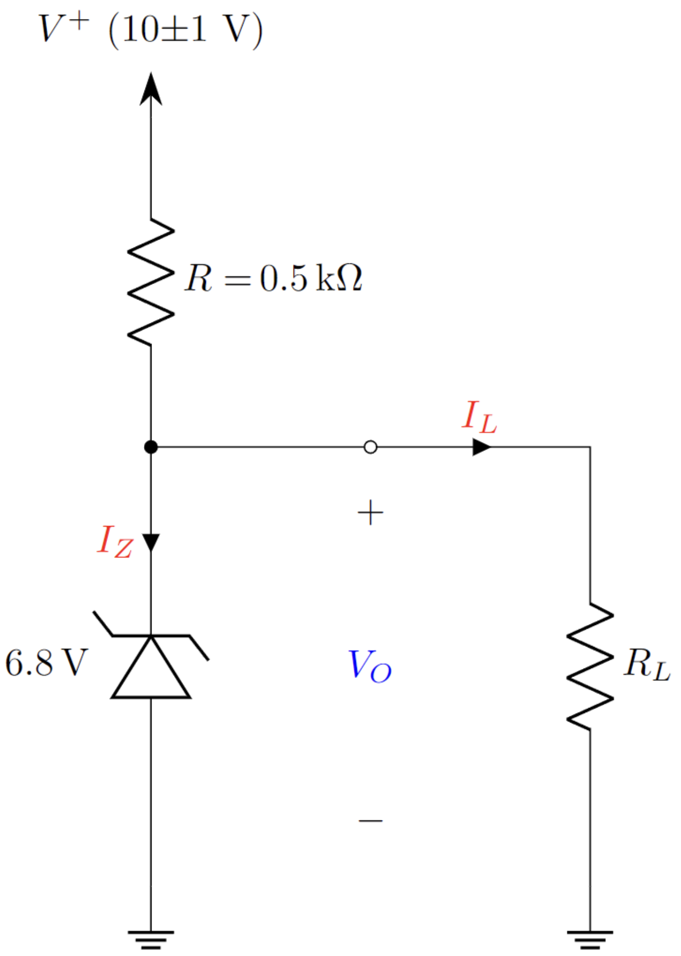
(b) (For $\boldsymbol{R_L} = \mathbf{0.5}\ \mathbf{k\Omega}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(c) Find the $\boldsymbol{R_L}$ that would give rise to worst-case scenario at worst case V^+. In this worst-case scenario, calculate the Zener voltage $\boldsymbol{V_Z}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(d) (For $\boldsymbol{R_L} = \mathbf{2}\ \mathbf{k\Omega}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

(e) Design the circuit, i.e., find the minimum value of the input voltage $\boldsymbol{V^+}$ such that, voltage regulation is maintained even in the worst-case scenario for $\boldsymbol{R_L} = 2\ \mathrm{k\Omega}$. (Forget that $\boldsymbol{V^+}$ is 10 V)

(f) Determine whether the circuit will maintain regulation if $\boldsymbol{V^+}$ is increased. If yes, argue if it should be increased or not.



Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

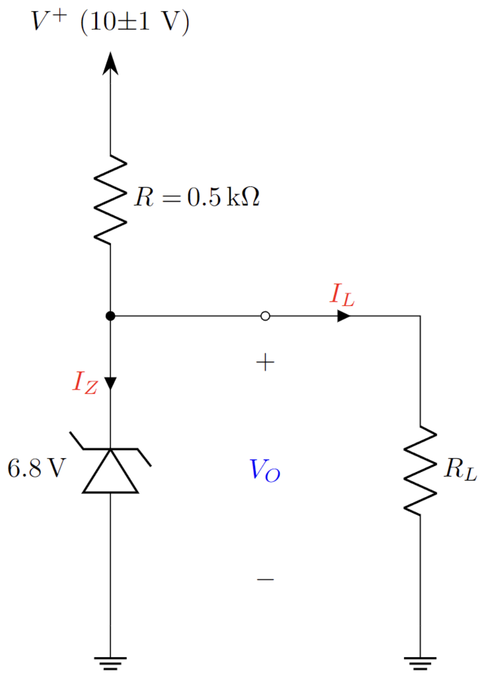
$V^+ = 10 \pm 1\,V$

$V_{Z1} = 6.8\,V$ at $I_{Z1} = 5\,mA$

$r_z = 20\,\Omega = 0.02\,\text{k}\Omega.$

$I_{ZK} = 0.2\,mA.$

(a) Find V_0 with no load and with V^+ at its nominal value



Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

$V_{Z1} = 6.8\,V$ at $I_{Z1} = 5\,mA$

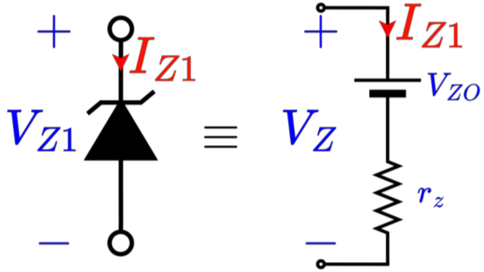
$r_z = 20\ \Omega = 0.02\ \text{k}\Omega.$

$I_{ZK} = 0.2\,mA.$

(a) Find V_0 with no load and with V^+ at its nominal value

Solution:

Extracting Zener diode 's reverse cut-in voltage



$$V_{ZO} = 6.8 - 5 \times 0.02\ \text{V}$$
$$\therefore V_{ZO} = 6.7\ \text{V}$$

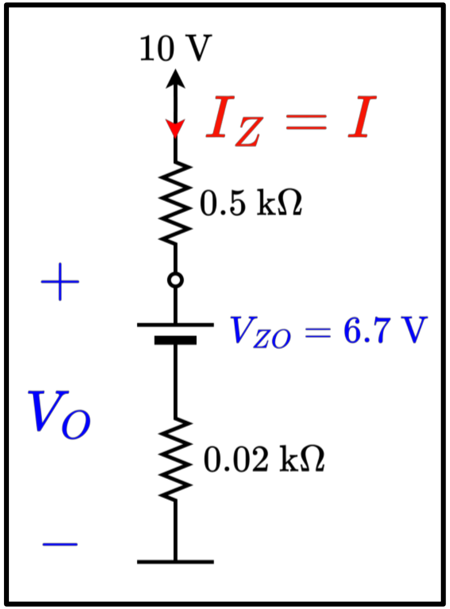
Determining current from the 10 V source

$$I = \underline{\qquad\qquad}$$

$$I = \frac{10 - 6.7}{0.5 + 0.02}\,\text{mA} = 6.346\ \text{mA}$$

Determining output voltage

$$V_O = 6.7 + 6.346 \times 0.02\ \text{V}$$
$$V_O = 6.82692\ \text{V}$$



Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

(b) (For $\boldsymbol{R_L = 0.5\ \mathrm{k\Omega}}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

Solution:

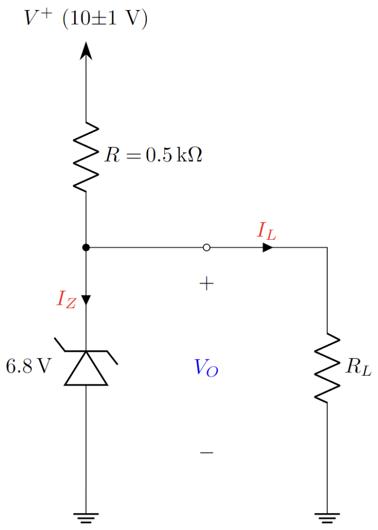
$V^+ = 10 \pm 1\,V$

$\cancel{V_Z = 6.8\,V \text{ at } I_Z = 5\,mA}$

$\boldsymbol{V_{ZO} = 6.7\ \mathrm{V}}$

$r_z = 20\ \Omega.$

$I_{ZK} = 0.2\,mA.$



Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$

$\cancel{V_Z = 6.8\,V \text{ at } I_Z = 5\,mA}$

$\mathbf{V_{ZO} = 6.7\ V}$

$r_z = 20\ \Omega.$

$I_{ZK} = 0.2\,mA.$

(b) (For $R_L = 0.5\ \mathrm{k\Omega}$). Find the I_Z. In this scenario, calculate the Zener voltage V_O, load current I_L and input current I

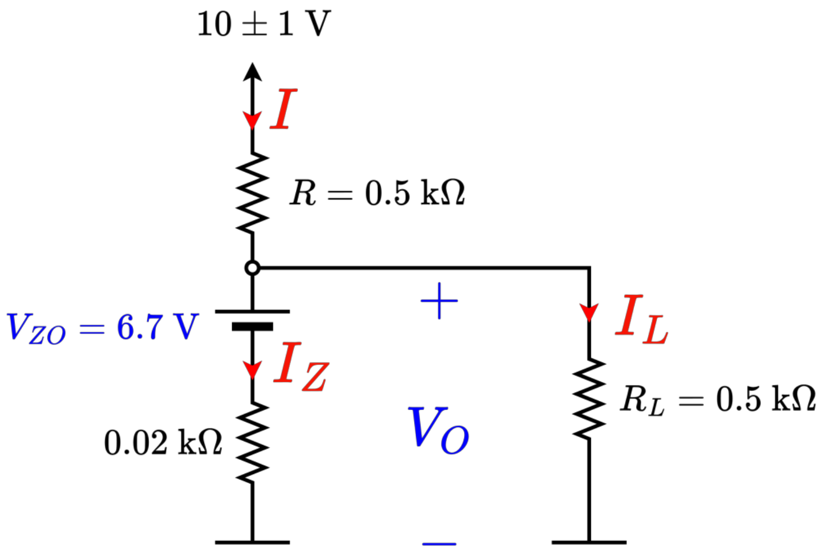
Solution:

Solving the node equation at V_O.

$$\frac{(10 \pm 1) - V_O}{R} = \frac{V_O - V_{ZO}}{r_z} + \frac{V_O}{R_L}$$

$$\frac{(10 \pm 1) - V_O}{0.5} = \frac{V_O - 6.7}{0.02} + \frac{V_O}{0.5}$$

$$\therefore V_O = 6.537 \sim 6.611\ \mathrm{V}$$



As, $V_O < V_{ZO}$, the Zener diode will be in cut off

$$I_Z = 0$$

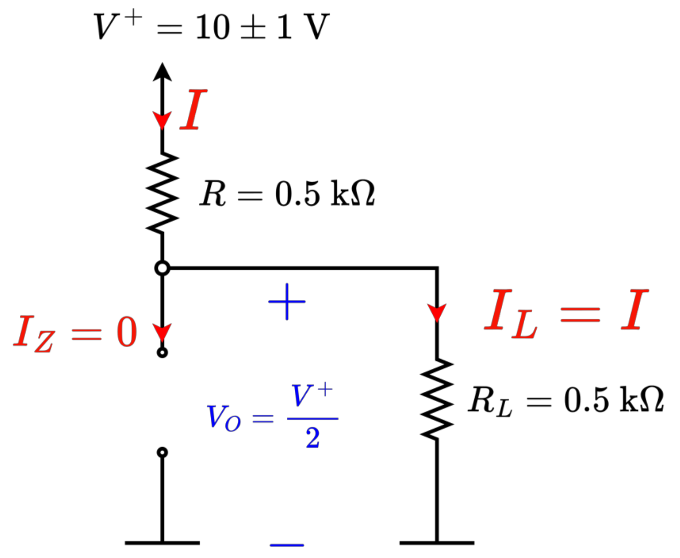
Practice Problem 2

The $6.8 - V$ Zener diode in the circuit of **Figure** is specified to have the following parameters. The supply voltage V^+ is nominally $\mathbf{10\ V}$ but can vary by $\pm\mathbf{1\ V}$.

$V^+ = 10 \pm 1\,V$
$\cancel{V_Z = 6.8\,V \text{ at } I_Z = 5\,mA}$
$\boldsymbol{V_{ZO} = 6.7\ \mathrm{V}}$
$r_z = 20\,\Omega.$
$I_{ZK} = 0.2\,mA.$

(b) (For $\boldsymbol{R_L = 0.5\ \mathrm{k\Omega}}$). Find the $\boldsymbol{I_Z}$. In this scenario, calculate the Zener voltage $\boldsymbol{V_O}$, load current $\boldsymbol{I_L}$ and input current $\boldsymbol{I}$

Solution:



So,

$$V_O = \frac{10 \pm 1}{2}\ \mathrm{V} = 5 \pm 0.5\ \mathrm{V}$$

$$I_Z = 0\ \mathrm{mA}$$

$$I_L = \frac{V^+ \pm 1}{R + R_L} = \frac{10 \pm 1}{1}\ \mathrm{mA} = \cancel{10\ \mathrm{mA}}\ \ 10 \pm 1\ \mathrm{mA}$$

(c) Find the R_L that would give rise to worst-case scenario at worst case V^+. In this worst-case scenario, calculate the Zener voltage V_Z, load current I_L and input current I

(d) (For $R_L = 2\ \text{k}\Omega$). Find the I_Z. In this scenario, calculate the Zener voltage V_O, load current I_L and input current I

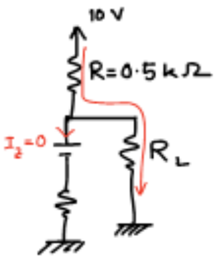
(c) The determining factor for worst-case scenario:

$I_z \geq I_{zK}$

$\therefore$ At $I_z = I_{zk}$ mA.

$V_o = V_{z0} + I_{zk} r_z = 6.704$ V

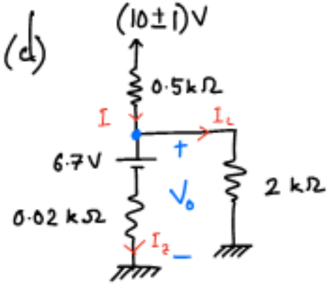
$\therefore$ $I = I_L + I_{zK}$.



$$\frac{10-1-V_o}{0.5k} = \frac{V_o}{R_L} + I_{zK}$$

$$\Rightarrow \frac{9-6.704}{0.5k} = \frac{6.704}{R_L} + 0.2\text{mA}$$

(d)



$I = I_z + I_L$

$$\frac{V^+ - V_o}{R} = \frac{V_o - V_{z0}}{r_z} + \frac{V_o}{R_L}$$

$$\Rightarrow V_o\left(\frac{1}{R} + \frac{1}{r_z} + \frac{1}{R_L}\right) - V_{z0}\left(\frac{1}{r_z}\right) = \frac{10}{R}$$

$$\Rightarrow V_o\left(\frac{1}{0.5} + \frac{1}{2} + \frac{1}{0.02}\right) = \frac{10}{0.5} + \frac{6.7}{0.02}$$

$$\Rightarrow V_o = \frac{355}{54}\ \text{V} = 6.76\ \text{V}$$

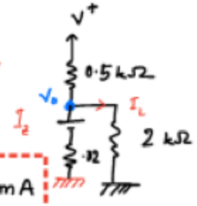
$$I_z = \frac{V_o - V_{z0}}{r_z} = \frac{6.76 - 6.7}{0.02} = 3.1\ \text{mA} > I_{zk}$$

So, the zener diode can sustain this load.

$\therefore$ $V_o = 6.76$ V

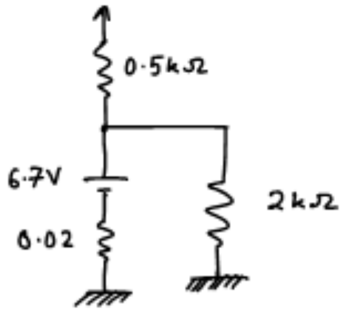
$I_z = 3.1$ mA

$I_L = \frac{6.76}{2}$ mA $= 3.38$ mA



(e) Design the circuit, i.e., find the minimum value of the input voltage $\boldsymbol{V}^+$ such that, voltage regulation is maintained even in the worst-case scenario for $\boldsymbol{R_L} = 2\ \mathrm{k\Omega}$. (Forget that $\boldsymbol{V}^+$ is 10 V)

(e)



At worst case : $I_z = I_{zK}$

$\therefore V_o = V_{z0} + I_{zK}\, r_z$

$= 6.7 + 0.2 \times 0.02 = 6.704\ V$

For $R_L = 2k\Omega$

$I_L = \dfrac{6.704}{2} = 3.352\ mA$

$I = I_L + I_{zk}$

$\boxed{I = 3.552\ mA}$

$\therefore V^+ \geq V_o + IR$

$\boxed{V^+ \geq 8.48\ V}$

Solving Problems

Modifiable Parameters

Circuit parameters .

$\boldsymbol{R, R_L}$

Zener diode parameters

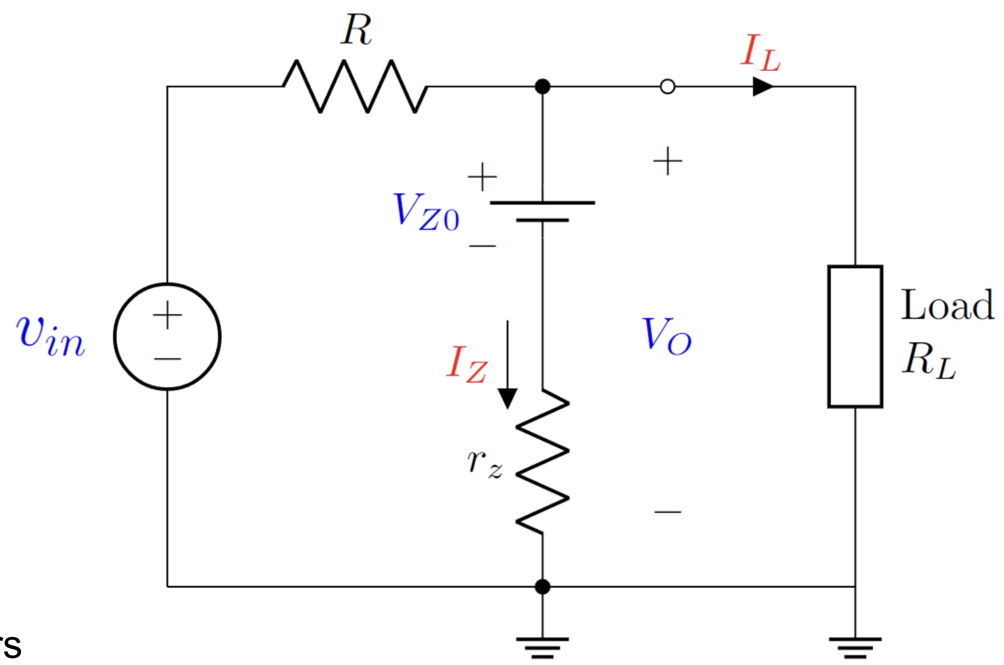
$\boldsymbol{V_{Z0}}$.

$\boldsymbol{r_z}$

Worst-Case Parameters

$\boldsymbol{I_{ZK}}$

Fixed Parameters



Obtain the Fixed Parameters first

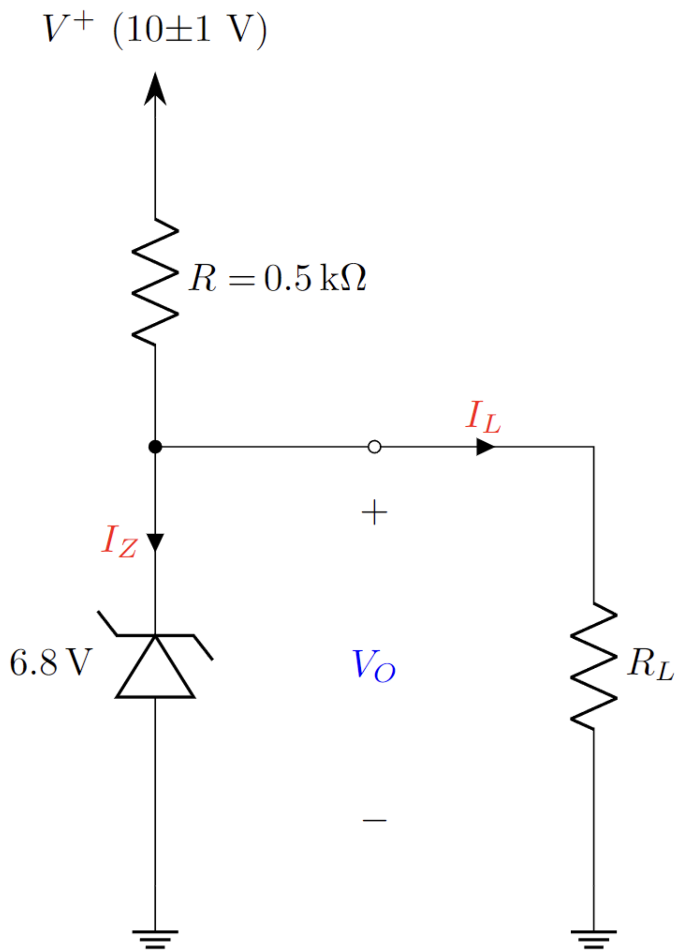
$$\boldsymbol{V_O} = \boldsymbol{V_{ZO}} + \boldsymbol{I_Z} r_z$$

$$I_Z = \frac{V_O - V_{ZO}}{r_z}$$

KCL/Nodal Analysis at node $\boldsymbol{V_O}$

$$\frac{v_{in} - V_O}{R} = I_Z + \frac{V_O}{R_L}$$

$$\frac{v_{in} - V_O}{R} = \frac{V_O - V_{ZO}}{r_z} + \frac{V_O}{R_L}$$



Practice Problem 3

The Zener diode in the circuit of **Figure** is specified to have the following parameters. The **supply voltage V_{in}** is nominally **$5\ V$** but can vary by **$\pm 10\ \%$.**
Load current can vary from $\mathbf{0}$ mA to $\mathbf{50}$ mA.

$V_{in} = 5\ \text{V} \pm 10\ \%$

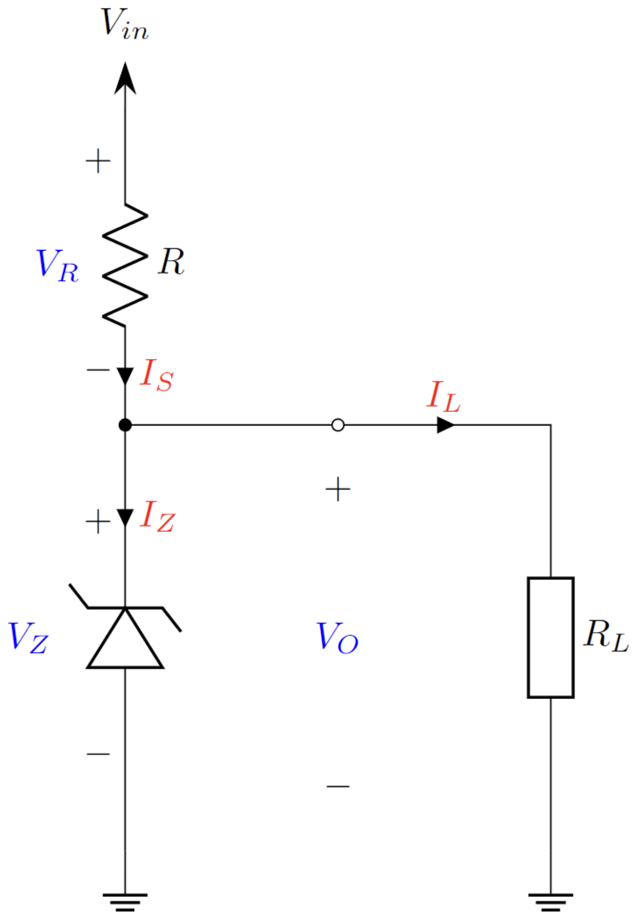
$V_{Z0} = 3\ V$
$r_z = 0\ \Omega$
$I_{ZK} = 1\ \text{mA}.$

a) Find **minimum and maximum input Voltage, $V_{in}(\text{min})$ and $V_{in}(\text{max})$, maximum and minimum load current $I_L(\text{max})$ and $I_L(\text{min})$, minimum diode current $I_Z(\text{min})$.**

b) Find the I_Z, V_{in} and I_L at worst-case scenario.

c) For worst case what is I_S and V_R.

d) Find R for which diode maintains regulation at worst case scenario



Practice Problem 4

The Zener diode in the circuit of **Figure** is specified to have the following parameters.

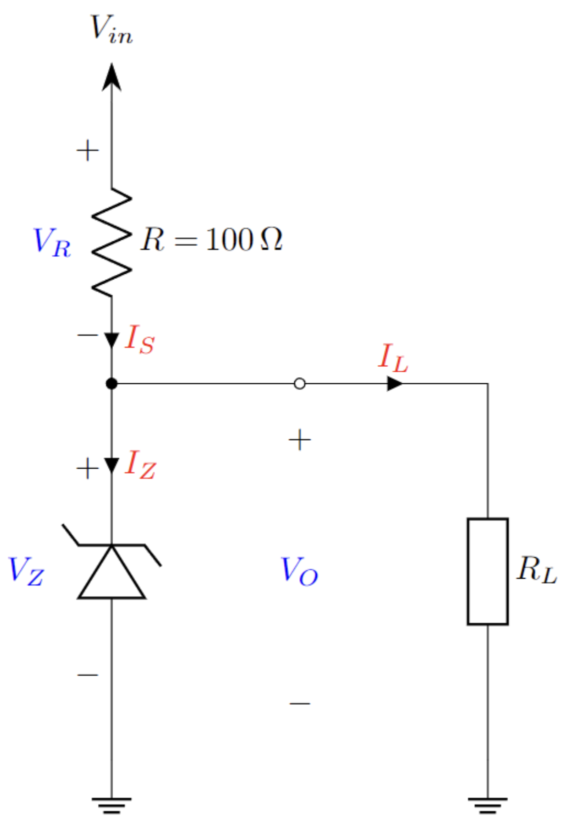
$V_{Z0} = 3\ V$

$r_z = 20\ \Omega, 0\ \Omega$

$I_{ZK} = 1\ \text{mA}.$

a) Find **minimum input voltage, $V_{in}(\text{min})$** for which the diode maintains regulation, when $R_L = 10\ \text{k}\Omega$.

b) Find worst case R_L if the **input voltage V_{in}** is nominally $5\ V$ but can vary by $\pm 10\ \%$



Some important tips

- If V_{ZK}, V_{ZO} and r_Z are given, we can calculate $I_{ZK} = \frac{V_{ZK} - V_{ZO}}{r_z}$

- If V_{ZO} and r_Z are **not** provided, consider $V_{ZK} = V_Z = V_{ZO}$

- Consider $I_{ZK} = 0$ if not provided