Bilkent University

EEE-313

Lab 2

Zener Regulator

Yiğit Narter

22102718

Section 01

I. Introduction

The purpose of this lab experiment is to construct a voltage regulator with a Zener diode. The source and load regulations will also be calculated. The circuit to be implemented is shown in Figure 1.

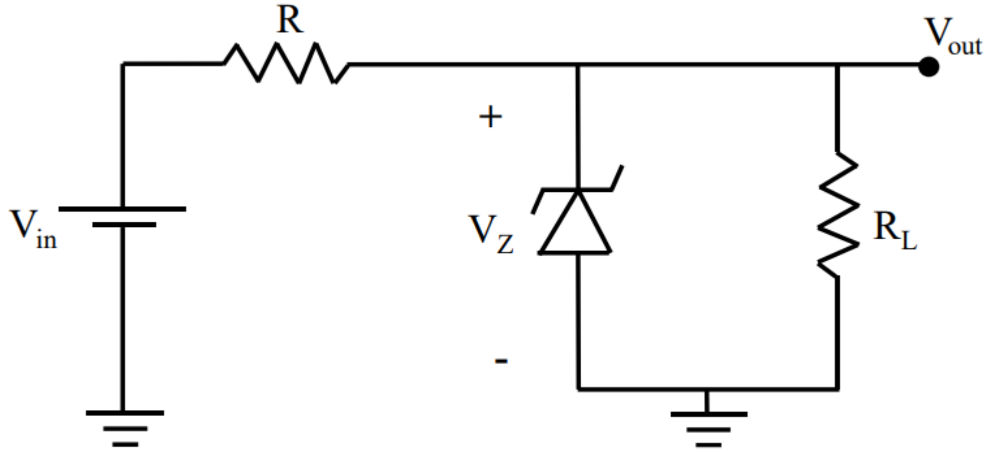

Figure 1: Circuit to be implemented

The components in the circuit are the Zener diode, R_L and R. The Zener diode is a 5.1 V no name Zener diode available in the lab. It is used in reverse bias to enable current flow in the opposite direction, and the Zener voltage is 5.1 V. R_L is the load resistance which is given as 500 Ω initially. R is the source resistance whose range is to be determined in the experiment, according to the minimum and maximum current values of the Zener diode. The input voltage V_{in} can be both a DC or AC signal. The experiment will involve both cases.

Zener diodes are highly doped semiconductors that can allow current flow in the reverse bias, unlike regular diodes. When the voltage across the diode is reversed and reaches the Zener voltage, a breakdown is observed at the junction, hence enabling the current flow in the opposite direction [1]. The minimum and maximum current passing through the Zener diode are determined by its operating conditions. The maximum current is determined by the Zener's power rating P_D, meaning the maximum power dissipation allowed. When this value is divided by the Zener voltage, the result is the maximum current. The minimum current is the required current in the reverse bias so that the diode is in the Zener region. It is usually indicated in the datasheet. The current is usually limited by a series resistor [1].

For the Zener voltage regulators, source regulation is the ability to maintain a stable output voltage as the input voltage changes [2]. Load regulation, on the other hand, is the ability to maintain a stable output as the load resistance, and hence the load current, is changing [3]. These values should be as low as possible to obtain a well-designed voltage regulator. With the help of Zener voltage regulators, unstable conditions such as voltage spikes and voltage drops can be prevented since the output voltage is regulated with the Zener diode. This ensures that the circuit components are operating as expected and are not being harmed, even when the input voltage is fluctuating.

The lab consists of three parts, first the range of resistance R should be found according to the Zener current's minimum and maximum values. Then the internal series resistance of the Zener diode (r_Z) and the source regulation will be found. Finally, the load regulation will be calculated.

II. Hardware Implementation and Analysis

- **Part A - Calculation of R's range**

In this part, the range of R should be found with the given conditions that the Zener current is between 10 mA and 100 mA, while the input voltage V_{in} varies between 9 V and 11 V. R_L is given as 500 Ω, and V_{in} is given as 10 V with +1 V and -1 V variance. The circuit to be worked on is given as:

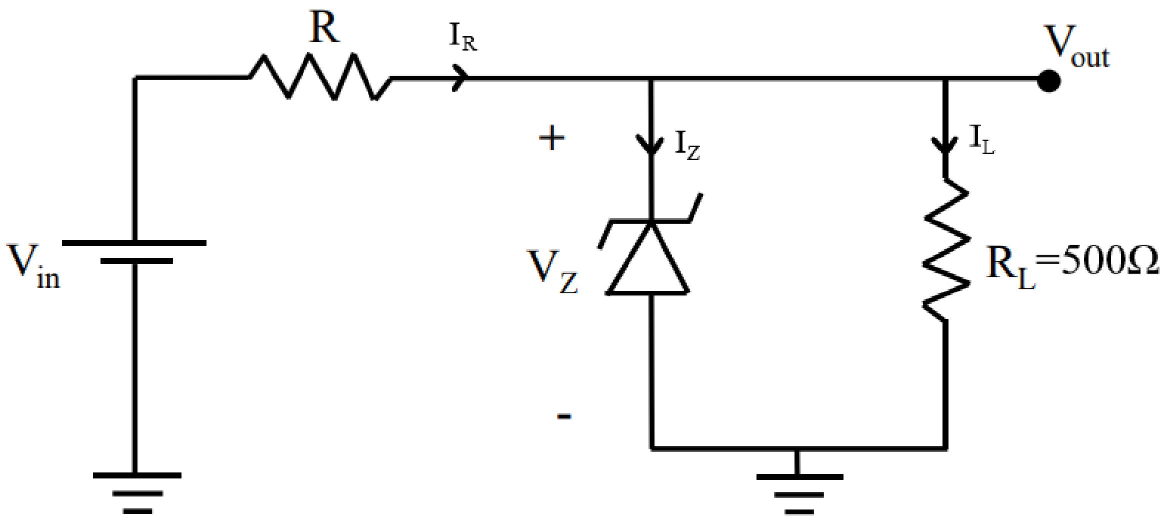

Figure 2: Circuit for part A

First, it is observed that the load current I_L can be found as:

$$I_L = \frac{V_Z}{R_L} = \frac{5.1V}{500\Omega} = 10.2\ mA \tag{1}$$

since the voltage on R_L is equal to V_Z = 5.1 V. It should also be noted that V_{out}=V_Z=5.1V. Then for the limits of the voltage, the R ranges can be calculated, considering the minimum and maximum current conditions.

- For V_{in}=9V:

When the current on the Zener is minimum (10 mA), I_z = 10 mA. Then by performing a KCL at the output node V_{out}:

$$I_R = I_L + I_Z = 10 + \ 10.2 = 20.2\, mA \tag{2}$$

Then, by Ohm's Law, since the voltage on R is V_{in}-V_{out}:

$$V_{in} - V_{out} = R * I_R \tag{3}$$

$$R_{max} = \frac{V_{in} - V_{out}}{I_R} = \frac{9V \ - \ 5.1V}{20.2\, mA} = 193\Omega \tag{4}$$

as V_{in}= 9V and V_{out} is equal to the Zener voltage 5.1V. This resistance value is the upper limit for R for V_{in}=9V. This is because with decreasing current on the resistor, the resistance should increase since the voltage across the resistor is constant (V_{in}= 9V and V_{out}=5.1V)

When the current on the Zener is maximum (100 mA), I_z = 100 mA. Then by performing a KCL at the output node V_{out}:

$$I_R = I_L + I_Z = 100 + \ 10.2 = 110.2\, mA \tag{5}$$

Then, by Ohm's Law, since the voltage on R is V_{in}-V_{out}:

$$V_{in} - V_{out} = R * I_R \tag{6}$$

$$R_{min} = \frac{V_{in} - V_{out}}{I_R} = \frac{9V \ - \ 5.1V}{110.2\, mA} = 35.4\Omega \tag{7}$$

as V_{in}= 9V and V_{out} is equal to the Zener voltage 5.1V. This resistance value is the lower limit for R for V_{in}=9V. Hence for V_{in}=9V, the value of R should vary between 35.4 Ω and 193 Ω to stay in the 10mA-100mA current range.

- For V_{in}=11V:

When the current on the Zener is minimum (10 mA), I_z = 10 mA. Then by performing a KCL at the output node V_{out}:

$$I_R = I_L + I_Z = 10 + \ 10.2 = 20.2\, mA \tag{8}$$

Then, by Ohm's Law, since the voltage on R is V_{in}-V_{out}:

$$V_{in} - V_{out} = R * I_R \tag{9}$$

$$R_{max} = \frac{V_{in} - V_{out}}{I_R} = \frac{11V - 5.1V}{20.2\,mA} = 292\Omega \tag{10}$$

as V_{in}= 11V and V_{out} is equal to the Zener voltage 5.1V. This resistance value is the upper limit for R for V_{in}=11V.

When the current on the Zener is maximum (100 mA), I_z = 100 mA. Then by performing a KCL at the output node V_{out}:

$$I_R = I_L + I_Z = 100 + 10.2 = 110.2\,mA \tag{11}$$

Then, by Ohm's Law, since the voltage on R is V_{in}-V_{out}:

$$V_{in} - V_{out} = R * I_R \tag{12}$$

$$R_{min} = \frac{V_{in} - V_{out}}{I_R} = \frac{11V - 5.1V}{110.2\,mA} = 53.5\Omega \tag{13}$$

as V_{in}= 11V and V_{out} is equal to the Zener voltage 5.1V. This resistance value is the lower limit for R for V_{in}=11V. Hence for V_{in}=11V, the value of R should vary between 53.5 Ω and 292 Ω to stay in the 10mA-100mA current range. The results are presented in Table 1.

	I_{min} = 10mA	**I_{min} = 100mA**
V_{in} = 9V	R_{max}=193 Ω	R_{min}=35.4 Ω
V_{in} = 11V	R_{max}=292 Ω	R_{min}=53.5 Ω

Table 1: R's calculated range

Lastly, taking the larger number for the lower limit and the smaller number for the upper limit, R's range is found as:

$$53.5\Omega < R < 193\,\Omega \tag{14}$$

Since it is in the desired range, I chose R as 120 Ω. With the selected value, I implemented the circuit on hardware as seen in Figure 3.

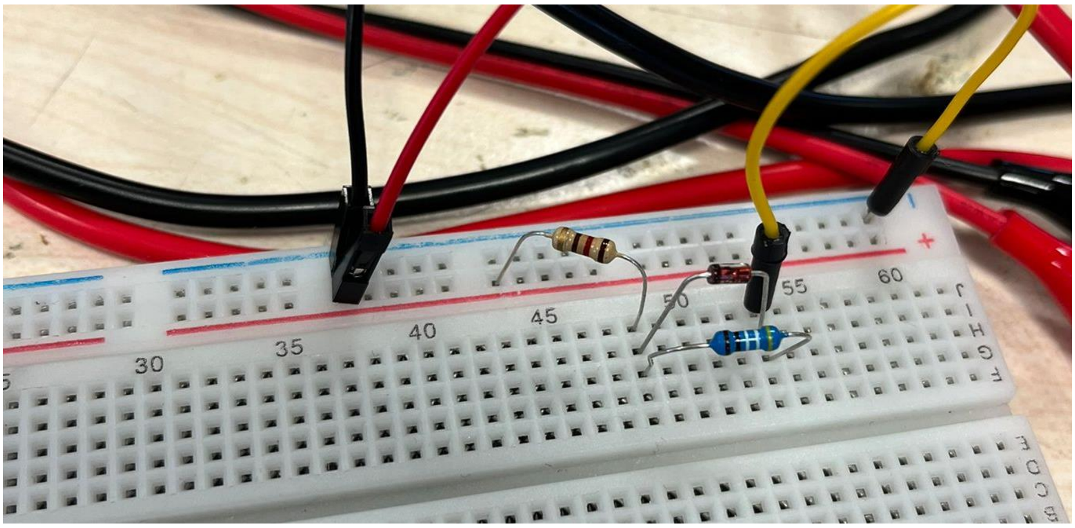

Figure 3: Circuit is implemented

After setting up the circuit, I measured the current on the Zener using a multimeter. The input voltage is varied from 9V to 11V. The measurements are shown below.

Figure 4: Current for V_{in}=9V

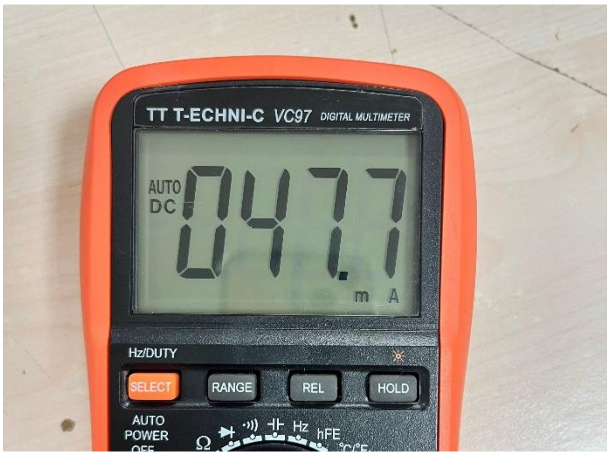

Figure 5: Current for V_{in}=11V

As seen from the results, the current is 28.16 mA for V_{in}=9V, and 47.7 mA for V_{in}=11V. As expected, the values are in the 10mA-100mA range hence they satisfy the current condition.

- **Part B - Calculation of Zener's inner resistance and source regulation**

In this part, V_{in} is selected as $V_{DC} + 0.1\sin\omega t$ V where f = 100 Hz and V_{DC} = 9.5 V. Zener diodes have internal series resistances, which plays a crucial role in their operation and their response to load variation [2]. It is a dynamic resistance, changing with factors like temperature and current [4]. Considering the resistance, a Zener diode can be modeled as follows:

Figure 6: Zener diode with resistance

This resistance can also be observed in the I-V curve of a non-ideal Zener diode:

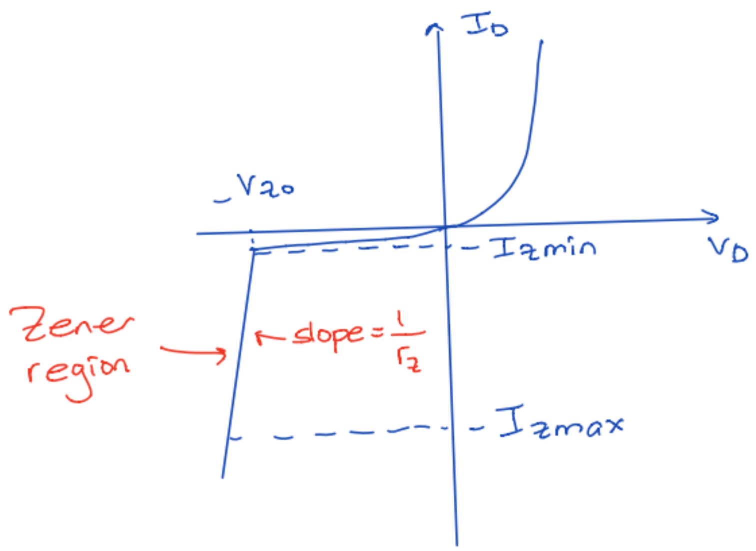

Figure 7: Non-ideal Zener I-V curve

In this part, now the signal generator's 50 Ω inner resistance (r_{in}) should also be considered. Hence, the circuit for this part becomes:

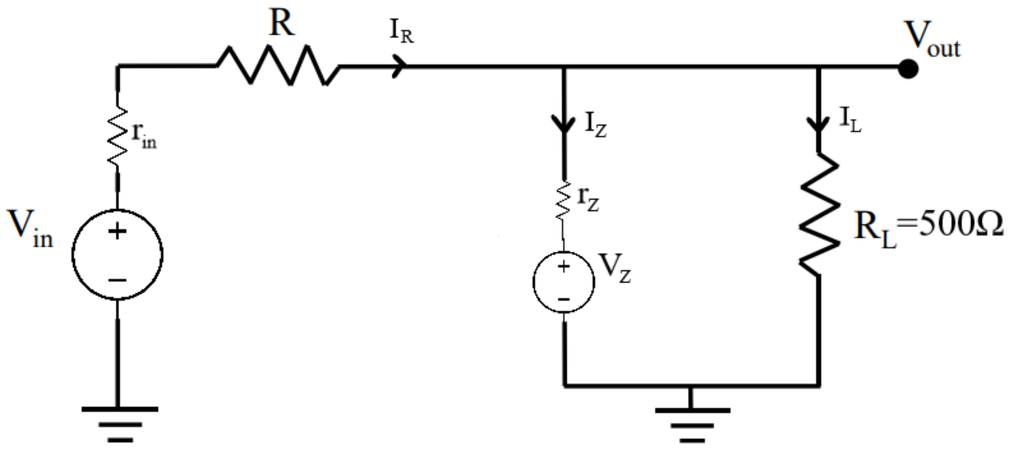

Figure 8: Circuit with r_Z

Here, R is the chosen value of 120 Ω, r_{in} is 50 Ω and V_Z is 5.1V. Now, to find r_Z, KCL at the output node V_{out} can be considered:

$$\frac{V_{out}-V_{in}}{R+r_{in}}+\frac{V_{out}-V_Z}{r_Z}+\frac{V_{out}}{R_L}=0 \tag{15}$$

The value of V_{out} is to be measured during the experiment. By rearranging the terms, r_z is found as:

$$r_Z=\frac{V_{out}-V_Z}{\frac{V_{in}-V_{out}}{R+r_{in}}-\frac{V_{out}}{R_L}} \tag{16}$$

Plugging in the values:

$$r_Z=\frac{V_{out}-5.1}{\frac{V_{in}-V_{out}}{170}-\frac{V_{out}}{500}} \tag{17}$$

The source regulation refers to the change in output voltage when the input voltage is fluctuating. It is defined as a percentage [2]:

$$Source\ regulation=\frac{\Delta V_{out}}{\Delta V_{in}}*100\% \tag{18}$$

To calculate the theoretical source regulation, the voltage source can be thought of as a combination of V_{in} and ΔV_{in}, the latter referring to the fluctuation. Since ΔV_{out} will occur due to ΔV_{in}, the other voltage sources in the circuit, namely V_{in} and V_Z, can be ignored. Hence this time, performing KCL at the output node gives:

$$\frac{\Delta V_{out} - \Delta V_{in}}{R + r_{in}} + \frac{\Delta V_{out}}{r_Z} + \frac{\Delta V_{out}}{R_L} = 0 \tag{19}$$

$$\Delta V_{out} = \Delta V_{in} * \frac{r_Z //R_L}{(r_Z //R_L) + R + r_{in}} \tag{20}$$

which is essentially a voltage divider. Inserting the ratio of $\Delta V_{out}/\Delta V_{in}$ into equation 18:

$$Source\ regulation = \frac{r_Z //R_L}{(r_Z //R_L) + R + r_{in}} * 100\% \tag{21}$$

Hence, source regulation can be calculated when r_Z is found. However, in the experiment, ΔV_{out} will be measured and ΔV_{in} is $0.1\sin(2\pi*100*t)$. After calculating the experimental and theoretical values, they will be compared.

First, to calculate the internal resistance, I gave 9.5V DC voltage as the input. The output voltage, in this case, is 5.15 V.

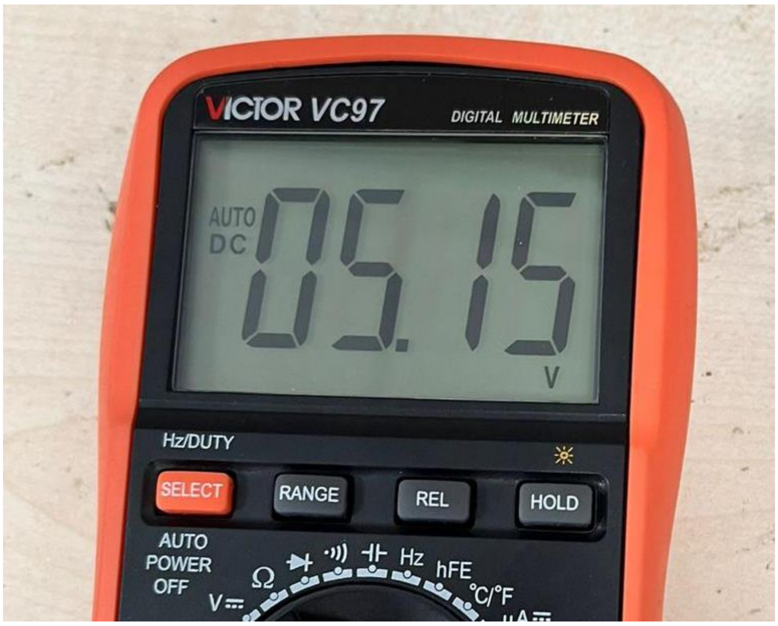

Figure 9: Output voltage is 5.15V

Inserting the values into equation 18, r_Z is found as:

$$r_Z = \frac{5.15-5.1}{\frac{9.5-5.15}{170}-\frac{5.15}{500}} = 3.27\ \Omega \tag{22}$$

Similarly, by equation 21, theoretical value of the source regulation is found as:

$$Source\ regulation = \frac{3.27\ //\ 500}{(3.27\ //\ 500)+170} * 100\% = 1.88\% \tag{23}$$

Both the internal resistance and the source regulation have small values, which is optimal for the Zener's operation and voltage regulation. After that, the circuit is set up again with the same values as the previous part:

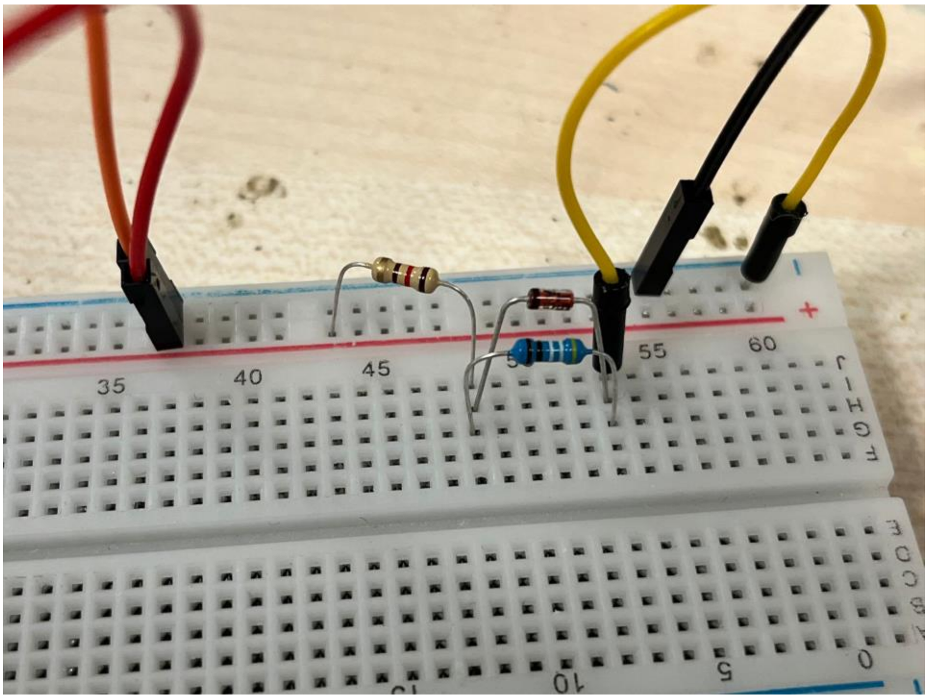

Figure 10: Circuit setup for part B

To obtain V_{in}, which is essentially a combination of a DC and AC voltage, I had to connect the DC voltage source and the signal generator together, since the signal generator's offset cannot reach 9.5V. To do that, I connected the ground of the DC voltage source to the positive terminal of the signal generator. Then I connected the signal generator's ground to the common ground. This way, two voltage sources are connected in series.

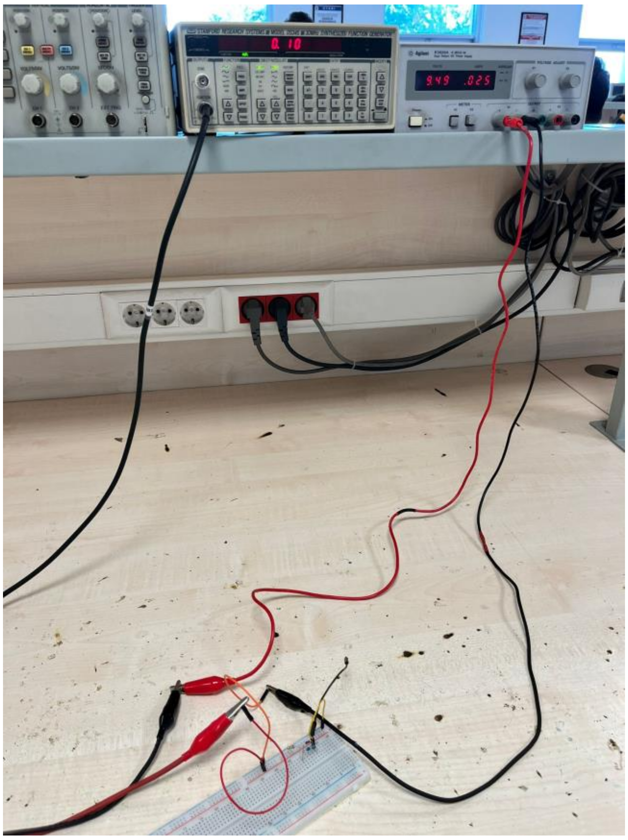

Figure 11: The setup for the voltage sources

Then, the DC part is set to 9.5 V and the AC signal is set to 0.1 V amplitude and 100 Hz frequency. However, when the output was measured, the signal was very unstable and hence the measurement had a risk of yielding big errors. To solve this problem, the AC part's amplitude is increased to 2 V. The input and output voltage measurements are shown below.

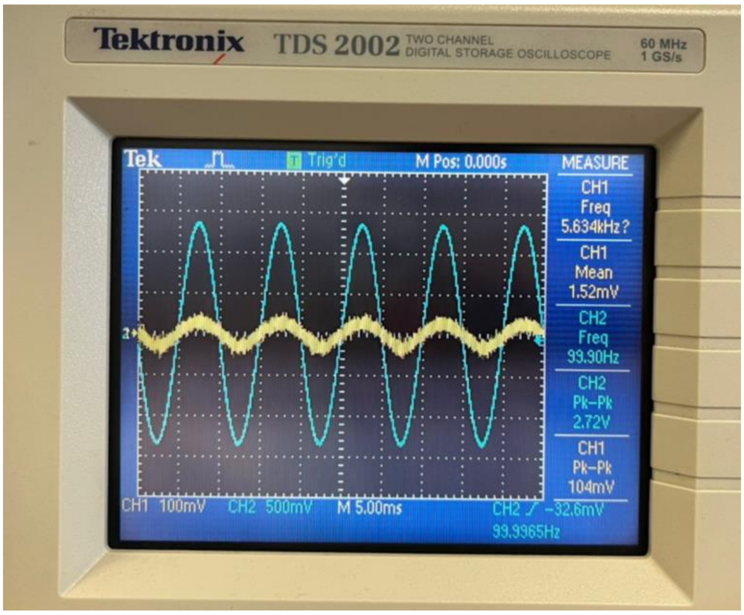

Figure 12: Input and output voltage

To measure the output, the oscilloscope coupling is set to AC, which eliminates the DC component of the output voltage. It should be noted that the peak-to-peak voltage (which is expected to be 4 V) is measured differently due to the internal resistance of the signal generator. In the calculations, however, since this resistance is also considered, the input peak-to-peak voltage will be taken as 4 V. Since the AC part of the signal actually corresponds to the variation among the input voltage, it can be thought of as ΔV_{in}, while the output voltage can be thought of as the response to this change, which is ΔV_{out}. For these values, the peak-to-peak voltages will be considered, which is 4V for the input and 104 mV for the output as seen in Figure 12. Placing these values into equation 18, the experimental source regulation is found as:

$$Source\ regulation = \frac{\Delta V_{out}}{\Delta V_{in}} * 100\% = \frac{104\ mV}{4\ V} * 100\% = 2.6\% \qquad (24)$$

which again, like the theoretical value, is a small number. The 0.72% difference between the two values may have occurred primarily due to the inner resistances of the signal generator and the DC voltage source, along with the way I connected them.

- **Part C - Calculation of load regulation**

Load regulation is essentially the percentage change in the Zener voltage regulator's output voltage for a given change in the load current. It is defined as [3]:

$$Load\ regulation = \frac{V_{out,no-load} - V_{out,full-load}}{V_{out,full-load}} * 100\% \qquad (25)$$

where $V_{out,no-load}$ is the output voltage with zero load current, and $V_{out,full-load}$ is the output voltage with full load current. For the experiment, the full load condition is given as 100Ω, and the input voltage V_{in} is 10V. The other values remain the same, hence R is 120Ω and r_Z is 3.27Ω as calculated in the previous part. The theoretical value for the load regulation therefore can be calculated, since the output voltages can be found using KCL.

For the no-load case, the load current I_L needs to be zero. This is equivalent to replacing R_L with an open circuit. Therefore, the circuit for this case becomes:

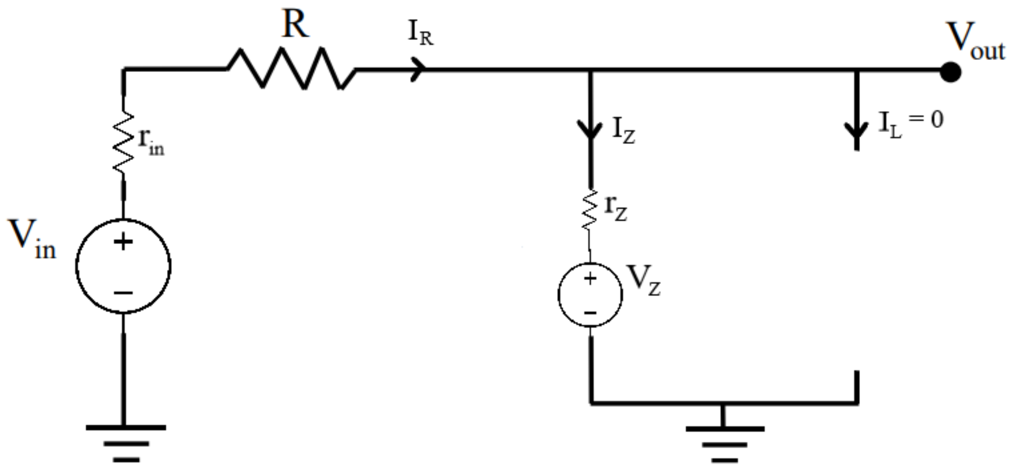

Figure 13: Circuit when I_L=0

Performing KCL at the output node and noting that I_L is zero:

$$\frac{V_{out,no-load} - V_{in}}{R + r_{in}} + \frac{V_{out,no-load} - V_Z}{r_Z} = 0 \tag{26}$$

Inserting the values:

$$V_{out,no-load}(\frac{1}{170} + \frac{1}{3.27}) = \frac{10}{170} + \frac{5.1}{3.27} \tag{27}$$

$$V_{out,no-load} = 5.192\ V \tag{28}$$

For the full-load case, the load current I_L needs to be maximum, and R_L should be set to 100Ω. Therefore, the circuit for this case becomes:

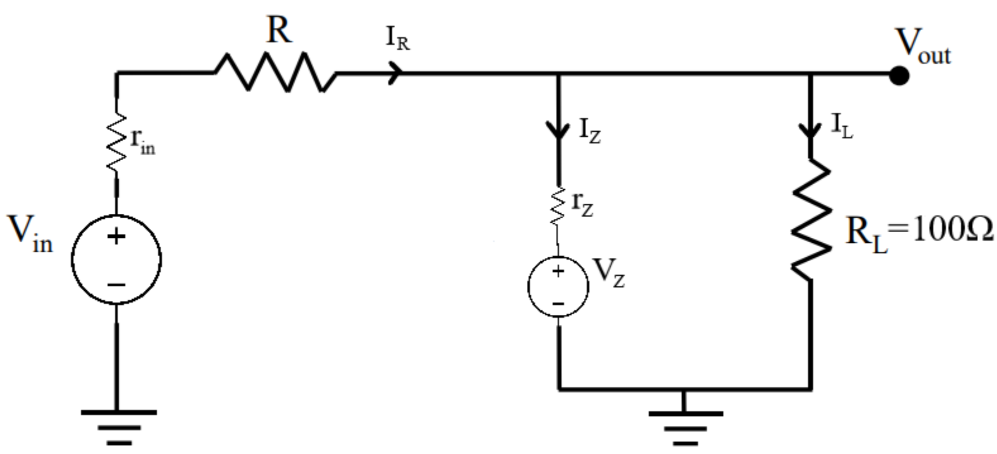

Figure 14: Circuit for maximum load case

Performing KCL at the output node:

$$\frac{V_{out,full-load} - V_{in}}{R + r_{in}} + \frac{V_{out,full-load} - V_Z}{r_Z} + \frac{V_{out,full-load}}{R_L} = 0 \tag{29}$$

Inserting the values:

$$V_{out,full-load}\left(\frac{1}{170} + \frac{1}{3.27} + \frac{1}{100}\right) = \frac{10}{170} + \frac{5.1}{3.27} \tag{30}$$

$$V_{out,full-load} = 5.031\,V \tag{31}$$

Finally, when the values are inserted into equation 25, the load regulation is calculated as:

$$Load\ regulation = \frac{5.192\,V - 5.031\,V}{5.031\,V} * 100\% = 3.2\% \tag{32}$$

The load regulation, like source regulation, is expected to have a small value, since the output should be as stable as possible as the load current varies. To calculate the experimental value of the load regulation, the no-load and full-load circuits are implemented on the breadboard and their output voltages are measured.

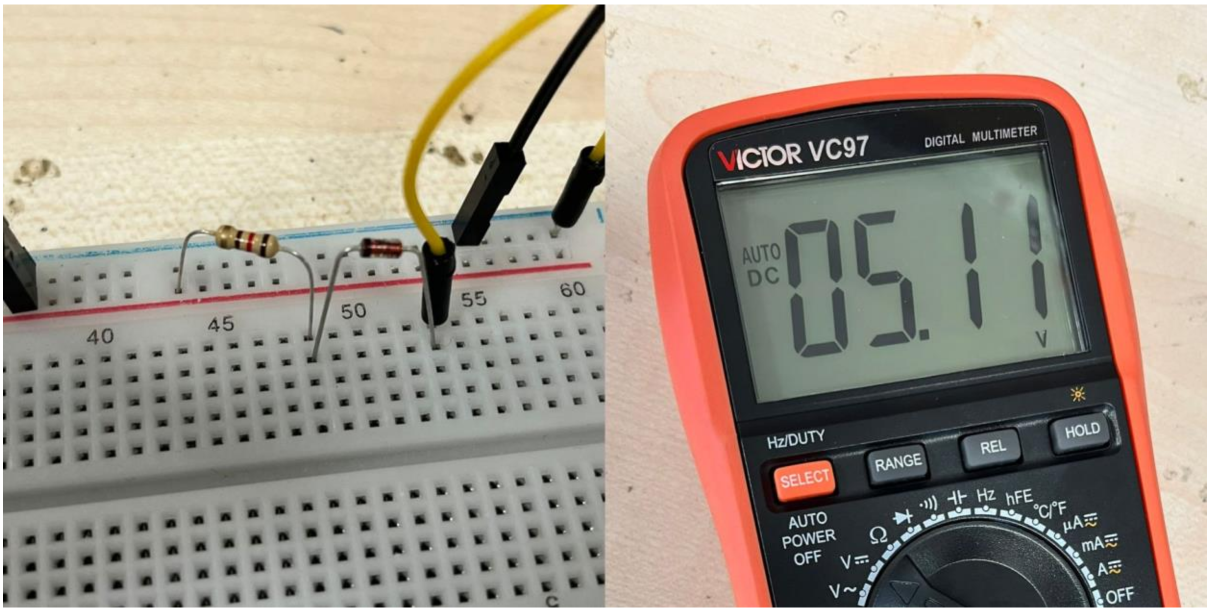

Figure 15: The no-load circuit and its output

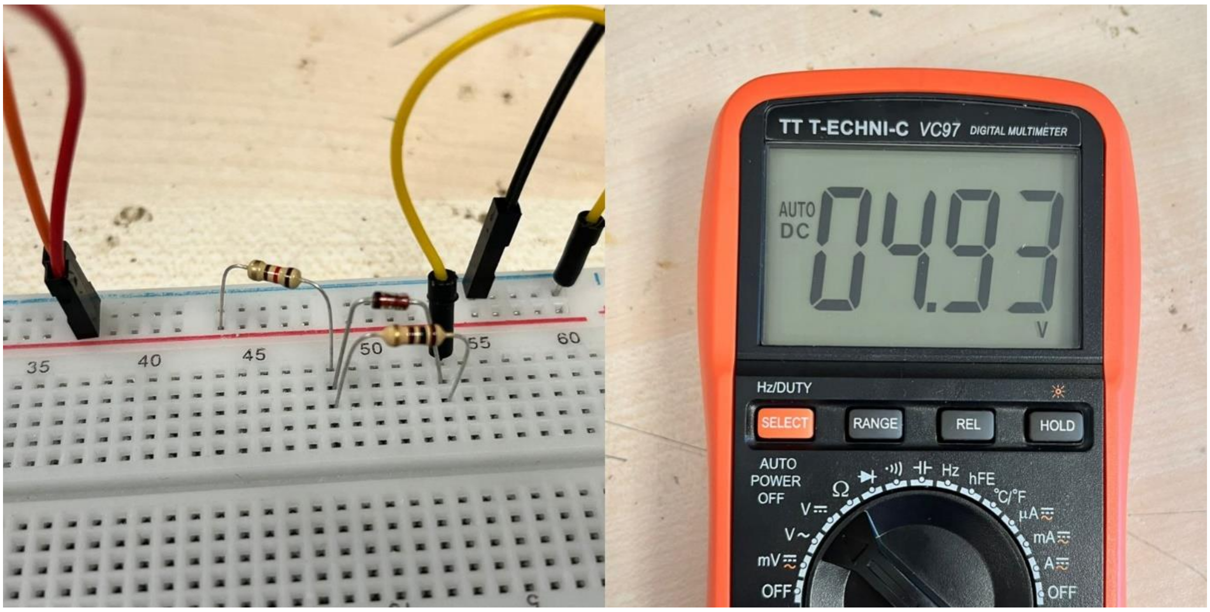

Figure 16: The full-load circuit and its output

For the no-load circuit, the output was measured as 5.11 V, while the full-load circuit's output was 4.93 V. Inserting these values into equation 25, the experimental load regulation is found as:

$$Load\ regulation = \frac{5.11\ V - 4.93\ V}{4.93\ V} * 100\% = 3.65\% \tag{33}$$

which is close to the theoretical value, with a 0.45% difference. The measurement devices being prone to measure small changes in the circuit may have contributed to the errors for both source and load regulations. Also, the inner resistance of the Zener diode being affected by the load current and temperature change, as well as the Zener diode's tolerance affect the circuit. These effects were not considered in the theoretical part. The final results are presented in Table 2.

	Theoretical value	**Experimental value**
Source regulation	1.88%	2.6%
Load regulation	3.2%	3.65%

Table 2: Final results for source and load regulations

III. Conclusion

This experiment's main purpose was to understand the operation of Zener diodes and the concept of voltage regulation. In the first part, to not exceed the power dissipation limit of the Zener which is 500 mW, the range of the resistance R was found with a given condition for the voltage. To not exceed the power limit and to ensure the diode is operating in the Zener region, the current should be in the range of 10 mA and 100 mA. As expected, the current remained in the interval as the voltage was increased from 9 V to 11 V.

In the second and third parts, the internal resistance of the Zener diode along with the source and load regulations were calculated. The inner resistance was found as 3.27 Ω, which is a small resistance indicating that the operation is very close to that of an ideal Zener. The expected source regulation was found as 1.88% and later in the experiment, it was found as 2.6%. During the measurement, the amplitude of the input AC voltage was increased to 2V to observe a less noisy output. The difference between the values is minimal and both values are small. This means that as the input source is varied, the output remains stable.

The load regulation was calculated as 3.2%, and the experimental value was found as 3.65%. The difference between the theoretical and the experimental values for both cases may have occurred due to several factors. First, the measurement devices can sometimes be prone to detecting small changes in the circuit. The resistors used in the circuit may not comply with their original resistance value, hence the current is affected. Also, the voltage sources' inner resistances and the way I connected the DC and AC voltage sources together can harm the accuracy.

Overall, this experiment taught me to implement a voltage regulator using a Zener diode circuit. Voltage regulation is an important concept in electrical engineering since output stability and protection are important to obtain successful operation. Zener diodes can be used for this purpose. By using the circuit analysis techniques I learned in the past, I was able to complete the experiment. In the future, I can integrate the knowledge I gained into more complex systems to regulate the output voltage.

References

[1] W. Storr, “Zener diode as voltage regulator tutorial,” Basic Electronics Tutorials, https://www.electronics-tutorials.ws/diode/diode_7.html (accessed Oct. 14, 2023).

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[4] “Zener Diodes,” IBEX Resources, https://ibex.tech/resources/geek-area/electronics/diodes/zener-diodes (accessed Oct. 14, 2023).