Constructor University Bremen

CO-526-B

Electronics Lab

Fall Semester 2023

Lab Experiment 2 – Diodes

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Place of execution: Room 54, Research I, Jacobs University, 28759 Bremen

Date of execution: 24th October 2023

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Introduction

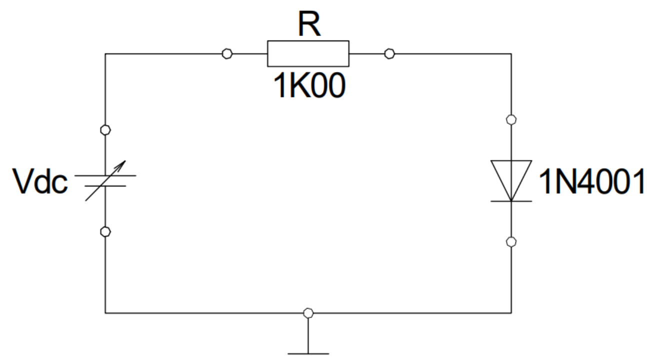
The experiment embarked on an exploration of semiconductor diodes, focusing specifically on rectifier diodes and Zener diodes and their diverse applications in various circuit configurations. The investigation delved into the properties of these diodes in the context of voltage regulators, clippers, and clampers. This report begins by outlining the theoretical foundation of diodes, detailing the creation of a diode through the combination of n-type and p-type semiconductor materials to form a PN junction. The diode encompasses two critical regions: the forward-biased and the reverse-biased. Under reverse bias, the diode exhibits characteristics wherein the current ideally approaches zero as the depletion zone expands. Conversely, applying positive voltage facilitates current flow through the diode by attracting electrons in the p-type region to the holes in the n-type region, illustrating the operational functionality of semiconductor diodes.

The experiment also incorporates Zener diodes into the circuits, which, while sharing similarities with regular semiconductor diodes, distinguish themselves in their response to reverse bias. In the reverse bias, a Zener diode maintains a constant saturation current until it reaches a breakdown voltage, leading to an exponential increase in current. Notably, the Zener diode operates in the reverse bias, specifically in the breakdown region, setting it apart from regular diodes. The subsequent sections of this report will delve into the prelab details, providing a comprehensive understanding of the experiment's theoretical underpinnings and preparatory steps.

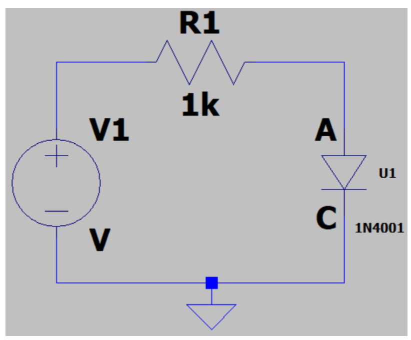
Prelab - Diodes

Problem 1 - Current/voltage characteristic of a diode

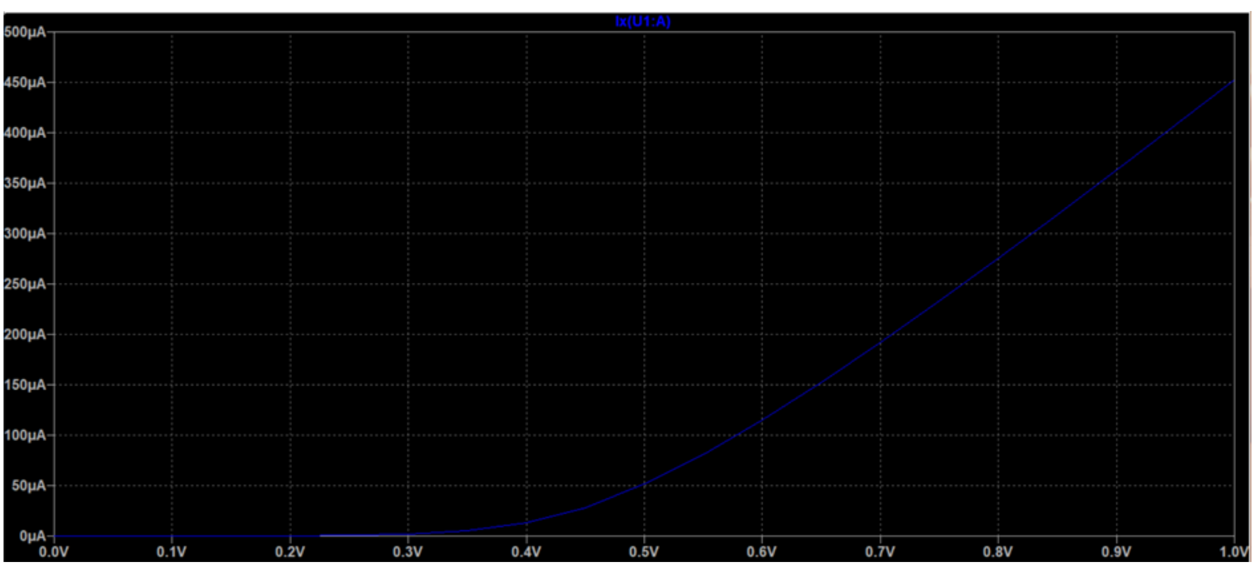
Implement the following circuit using LTSpice:



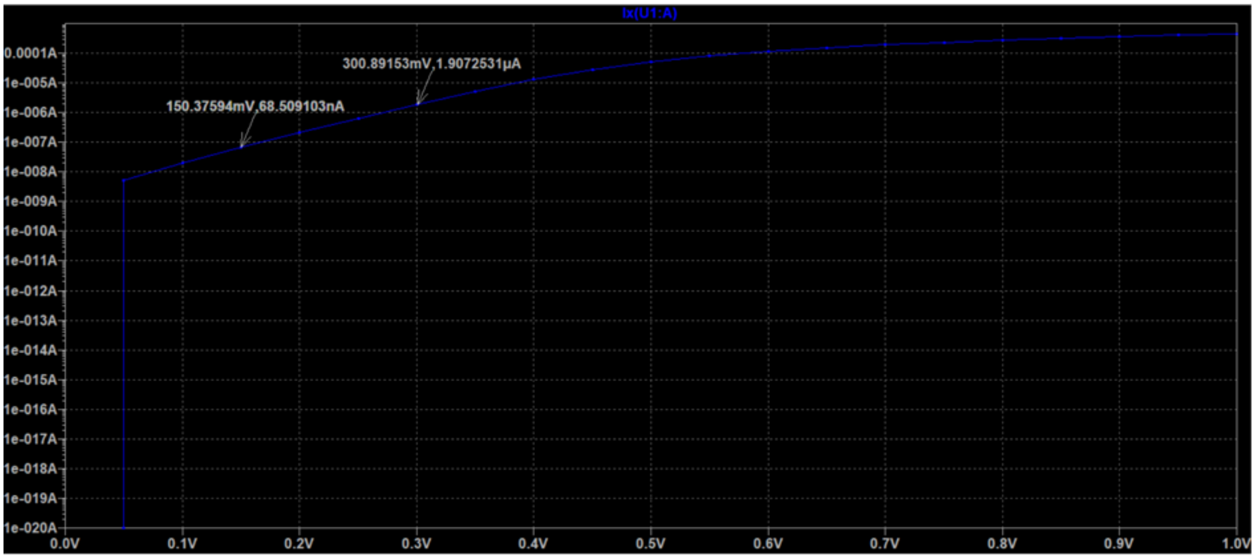
When implemented in LTSpice, it looks as follows:



Perform a DC sweep analysis:
Plot the diode characteristic $I_f = f(V_f)$



Plot the diode characteristic log(I_f)= f(V_f)



Extract the values of ideality or diode factor, n, and the saturation current I_s from the graph. The voltage V_T can be assumed to be 26mV

$$I = I_s e^{\frac{V}{nV_T}}$$

$$ln(I) = ln(I_s) + \frac{V}{nV_T}$$

Now, let $y = ln(I_s), x = \frac{1}{n}$

$$ln(I) - y = x\frac{V}{V_T}$$

Getting two points from the graph:

$(150.37mV, 68.51nA)$ and $(300.89mV, 1.91\mu A)$

We can solve the system of linear equations:

$$ln(0.00000006851) - y = x\frac{(0.15037)}{0.026}$$

$$ln(0.00000191) - y = x\frac{(0.30089)}{0.026}$$

We get:

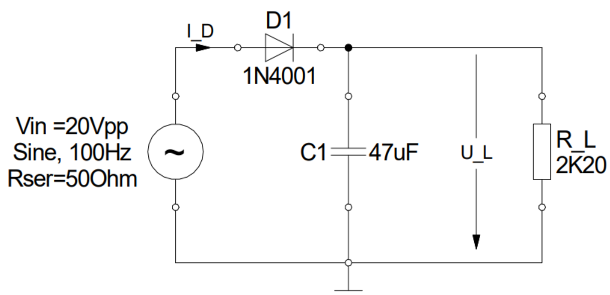
$$x = 0.575, y = (-19.821)$$

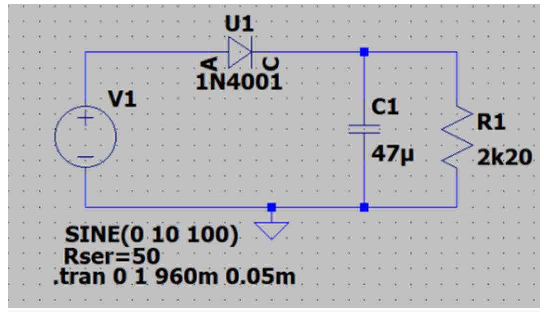
Then:

$$n = 1.7396, I_s = 2.4656 \cdot 10^{-9}A$$

Problem 2 - Halfwave rectifier

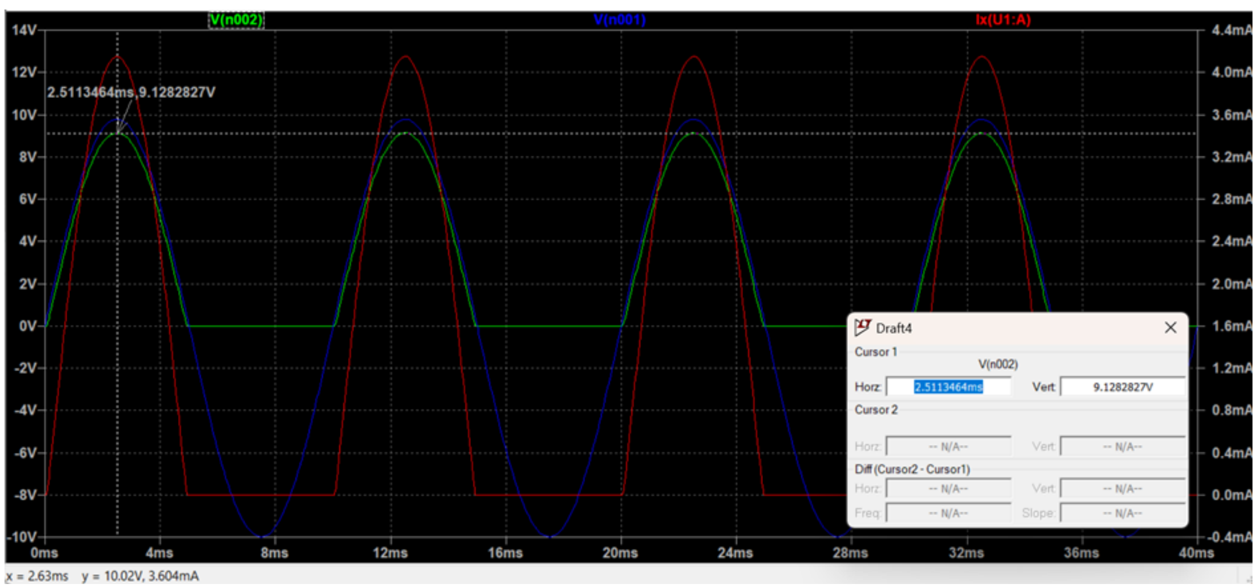
Implement the following circuit using LTSpice:



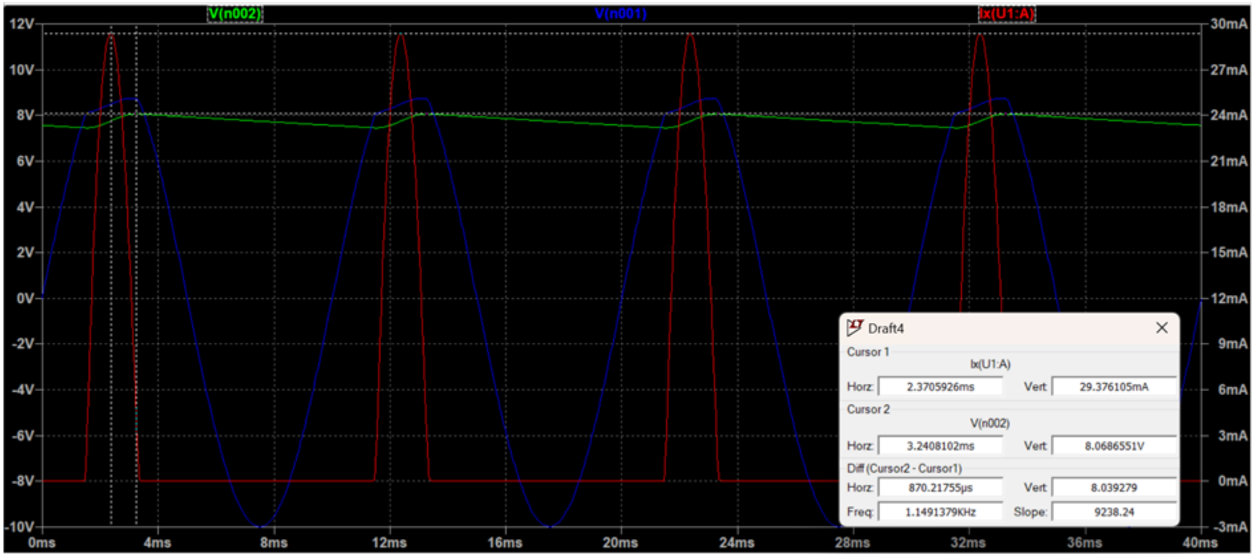


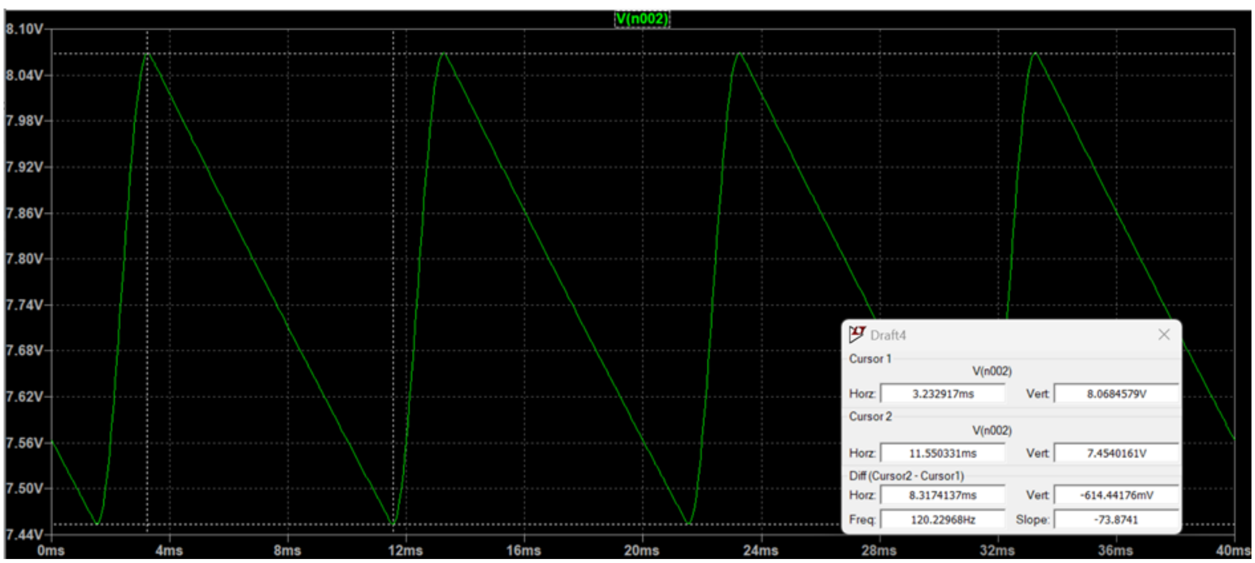
Perform a transient analysis (4 cycles of the sinusoidal input) for all following cases. Use the following parameters: .tran 0 1 960m .05m

Simulate the circuit without C_1. Plot V_L, V_{in} and I_D. Measure the peak voltage at R_L and the peak current I_D. Hint: Use the cursors from the LTSpice display



Simulate the circuit with C_1 connected. Plot V_L, V_{in} and I_D. Measure the peak voltage at R_L, the peak current I_D, and the ripple of the voltage V_L at the load resistor. Use the formula from the handout to calculate the ripple value. Compare!





The ripple voltage is 614.44mV

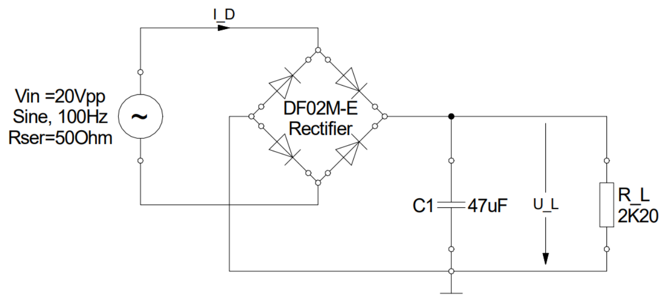
The theoretical ripple voltage can be calculated as:

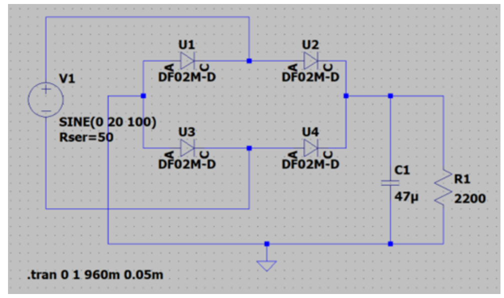
$$V_r = \frac{V_p}{fCR_L}\left(1 - \sqrt[4]{\frac{R_i}{R_L}}\right) = \frac{10}{(100)(47\cdot10^{-6})(2200)}\left(1 - \sqrt[4]{\frac{50}{2200}}\right) = 591.61mV$$

The simulated value is close to the theoretical value. Differences may have been caused by errors in cursor precision.

Problem 3 - Full wave rectifier

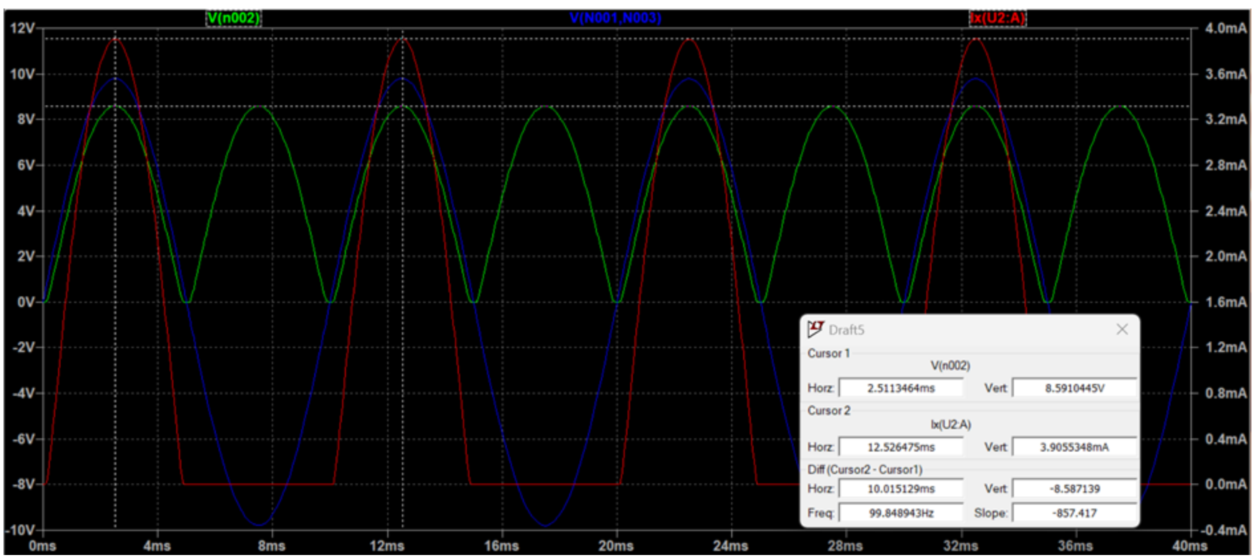
Implement the following circuit using LTSpice:



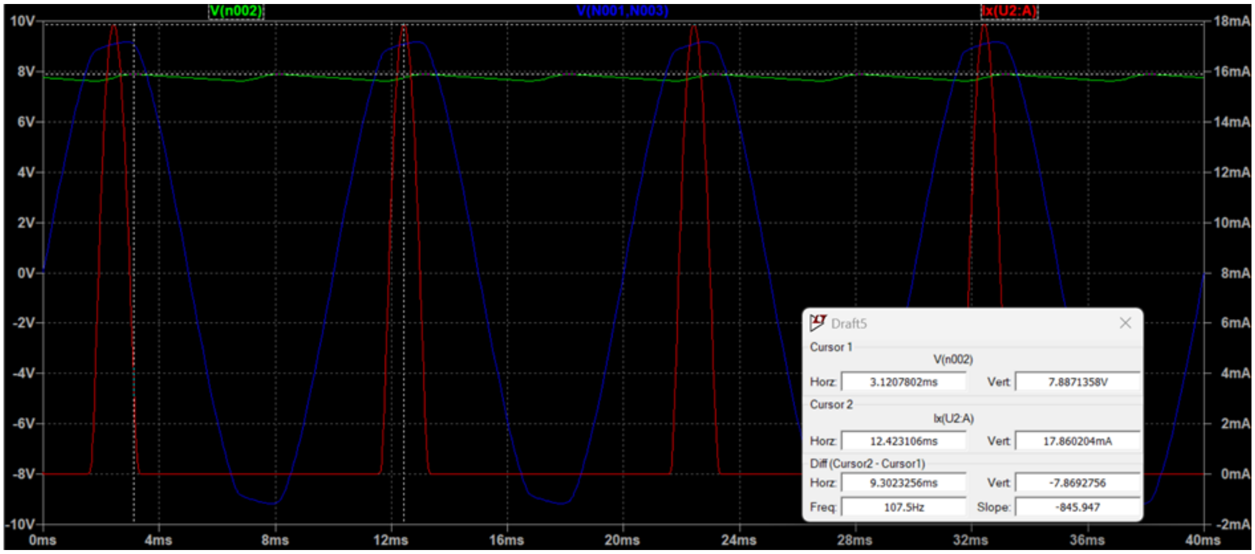


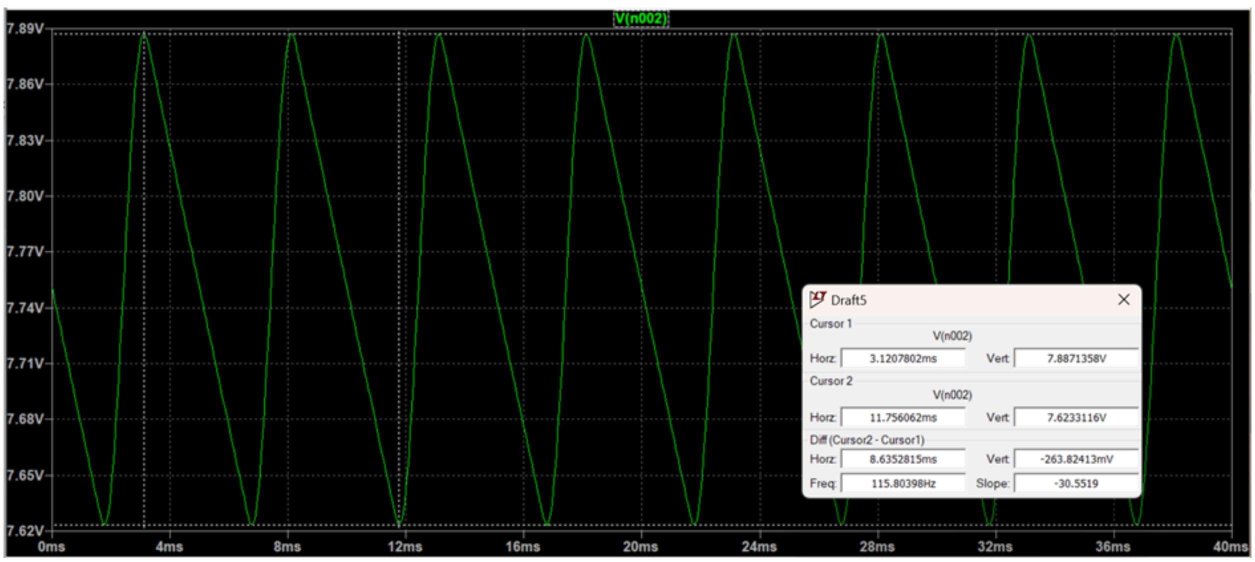
Perform a transient analysis (4 cycles of the sinusoidal input) for all following cases. Use the following parameters: .tran 0 1 960m .05m

Simulate the circuit without C_1. Plot V_L, V_{in} and I_D. Measure the peak voltage at R_L and the peak current I_D. Hint: Use the cursors from the LTSpice display



Simulate the circuit with C_1 connected. Plot V_L, V_{in} and I_D. Measure the peak voltage at R_L, the peak current I_D, and the ripple of the voltage V_L at the load resistor. Use the formula from the handout to calculate the ripple value. Compare!





The ripple voltage is 263.82mV

The theoretical ripple voltage can be calculated as:

$$V_r = \frac{V_p}{2fCR_L}\left(1 - \sqrt[4]{\frac{R_i}{R_L}}\right) = \frac{7.887}{2(100)(47\cdot10^{-6})(2200)}\left(1 - \sqrt[4]{\frac{50}{2200}}\right) = 233.32mV$$

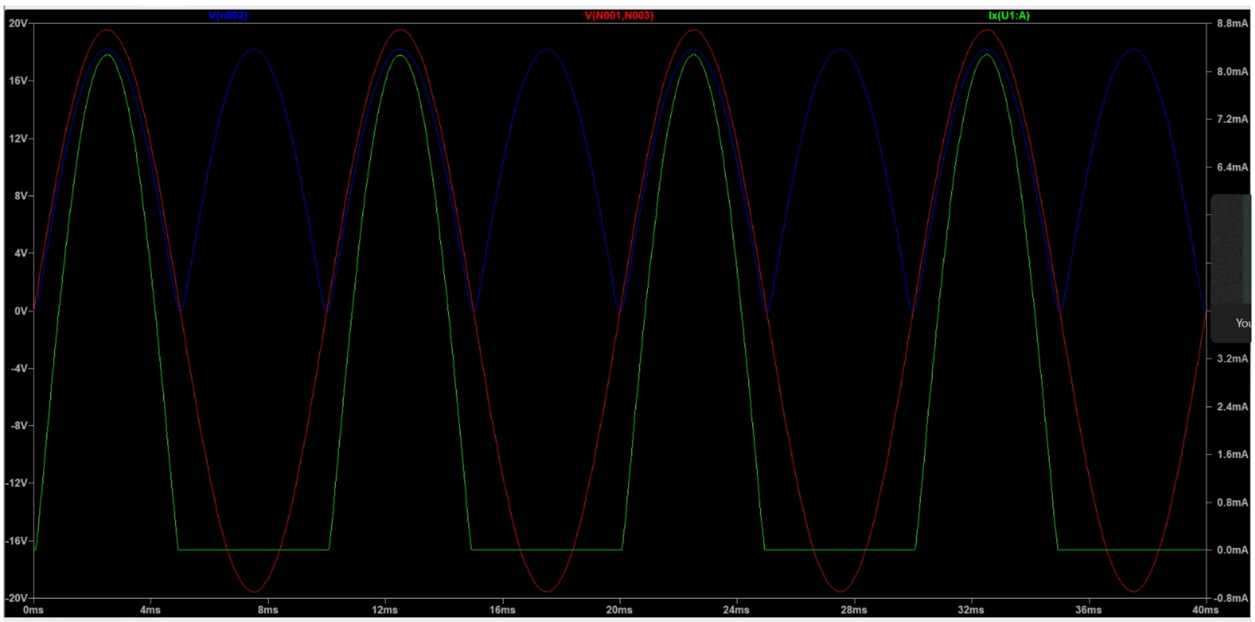
The simulated value is again close to the theoretical value. Differences may have been caused by errors in cursor precision.

Problem 4 - Rectifier

Explain the general function of the rectifier circuit with capacitor. Use simple principle circuit diagrams and the hard copies from the simulation to prove your statements!

A rectifier is a device that is used to convert a two-directional AC signal to a single-dimensional DC signal.

For example, when a two-directional oscillating AC sine wave is passed through a rectifier, the output is a single-directional signal, as shown below:



In the diagram above, V(n002) is the output directly out of the rectifier and V(N001, N003) is the input. As we see, the input signal changes direction, but the output signal doesn't. Although the output flows in a single direction now, it's not useful because of the large leaps in the single-directional output. The time-based variation in the output is too large. This issue is countered by using a capacitor, which acts as a smoothing filter. It smoothens the output curve by charging when the voltage across the load is higher than the voltage of the capacitor and discharging when the voltage across the load is lower than that of the capacitor. Ideally, the DC signal would become a flat line, which signifies a constant DC voltage. However, in our simulation, the filtering process is not perfect, so we are left with a ripple in the output.

1. **What are the maximum peak voltages without a capacitor at the load for each rectifier (in our case!)? Why are these values different from the input sine amplitude? Why is there a difference between half- and full-wave rectifier?**

Half wave rectifier:

Without capacitor: Peak voltage across R_L = 9.13V

With capacitor: Peak voltage at R_L = 8.07V

Full wave rectifier:

Without capacitor: Peak voltage at R_L = 8.59V

With capacitor: Peak voltage at R_L = 7.89V

There are voltage drops across the diodes and the internal resistance of the signal generator, causing the load to receive less than the full input signal. Consequently, the measured values differ from the input sine amplitude. In the half-wave rectifier, employing a single diode results in the complete cancellation of negative half-cycles, leading to capacitor discharge during those spans and producing a substantial ripple. On the other hand, the full-wave rectifier employs a diode network (with 4 diodes) to invert negative input cycles, ensuring that a positive cycle promptly follows the conclusion of the preceding one. This design leads to shorter discharge periods for the capacitor and more frequent full charges, resulting in a smoother output and a reduced ripple.

2. **Explain the differences in the current I_D for all cases. What is the consequence for the used diode in a rectifier circuit?**

The current through the diode is influenced by the presence of a capacitor and the type of rectifier device in use, with the existence of a rectifier leading to larger current amplitudes. In the presence of a capacitor, current flows through the load and diode during forward biasing, while no current flows otherwise. Continuous current flows through the load when a capacitor is present, with forward-biased diodes allowing current flow due to the source, resulting in capacitor charging. Conversely, during reverse biasing, the capacitor discharges onto the load, inducing a current flow.

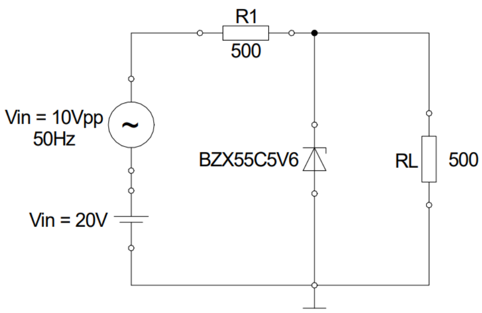
Additionally, the amplitude of current in a half-wave rectifier circuit surpasses that in a full-wave rectifier circuit. Another consequence of the diode's presence is that the input voltage is divided between the resistor and the diodes in series, leading to an overall output voltage lower than the input voltage.

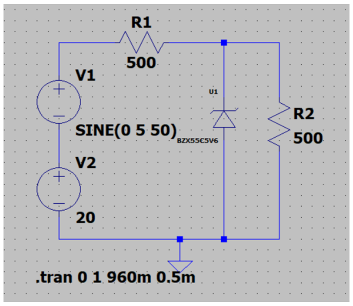
3. **What is the influence of the ratio $C * R_L$ to the quality of the output DC?**

The larger the ratio $C * R_L$, the smoother the DC output or the smaller the ripple. As a result, we have a better filter.

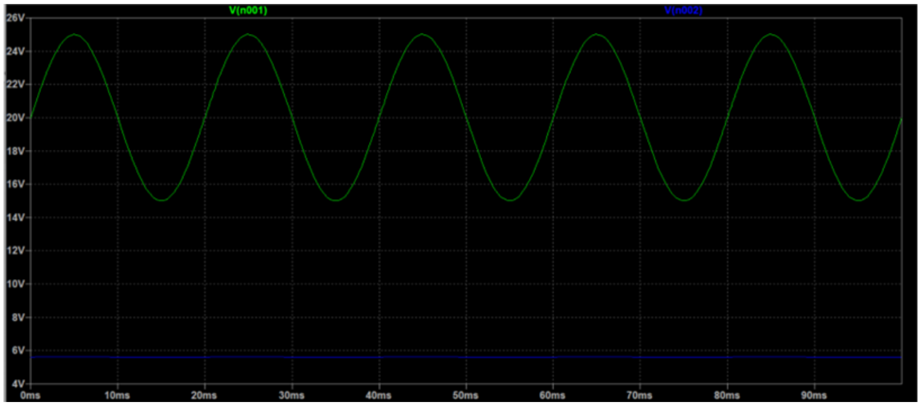
Problem 5 - Zener Diode

Implement the following circuit using LTSpice:





Perform a transient analysis (5 cycles of the sinusoidal input). Plot the input voltage (DC + AC voltage) and the output voltage across the load resistor R_L. Explain the operation of the circuit.



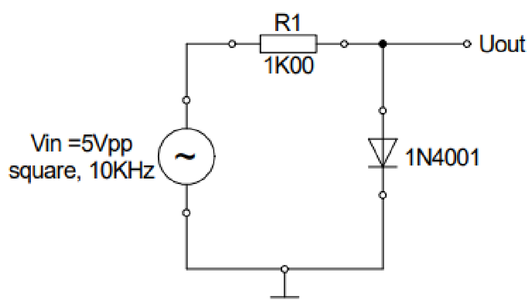
This is a voltage regulator circuit, ensuring a constant voltage and current across the load, irrespective of variations in the input voltage and current. The simulation reveals that despite substantial fluctuations in the input voltage of the load, the voltage across the resistor remains relatively stable (approximately 5.5V, with a current of around 11.2mA). The Zener diode adjusts its current consumption to maintain this stability under varying conditions.

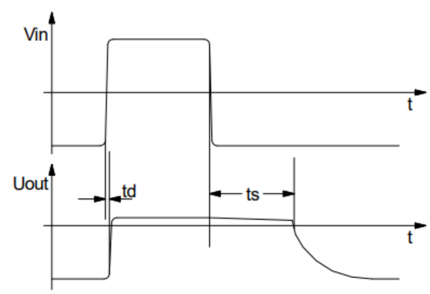
Experimental Set-up and Results

Part 1 - Diode Switching Characteristic

Experimental Setup and Procedure

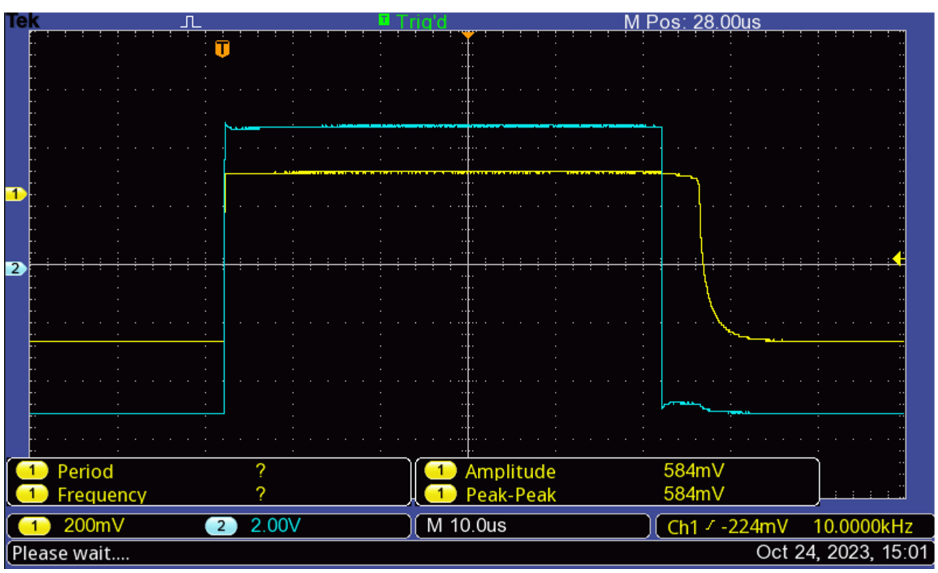
The goal of the experiment is to investigate the reverse/forward and forward/reverse transition behavior of a rectifier and a signal diode. Assemble the following circuit (left figure) on the breadboard. There is a delay time during reverse/forward transition and a storage time after forward/reverse transition. (right figure)





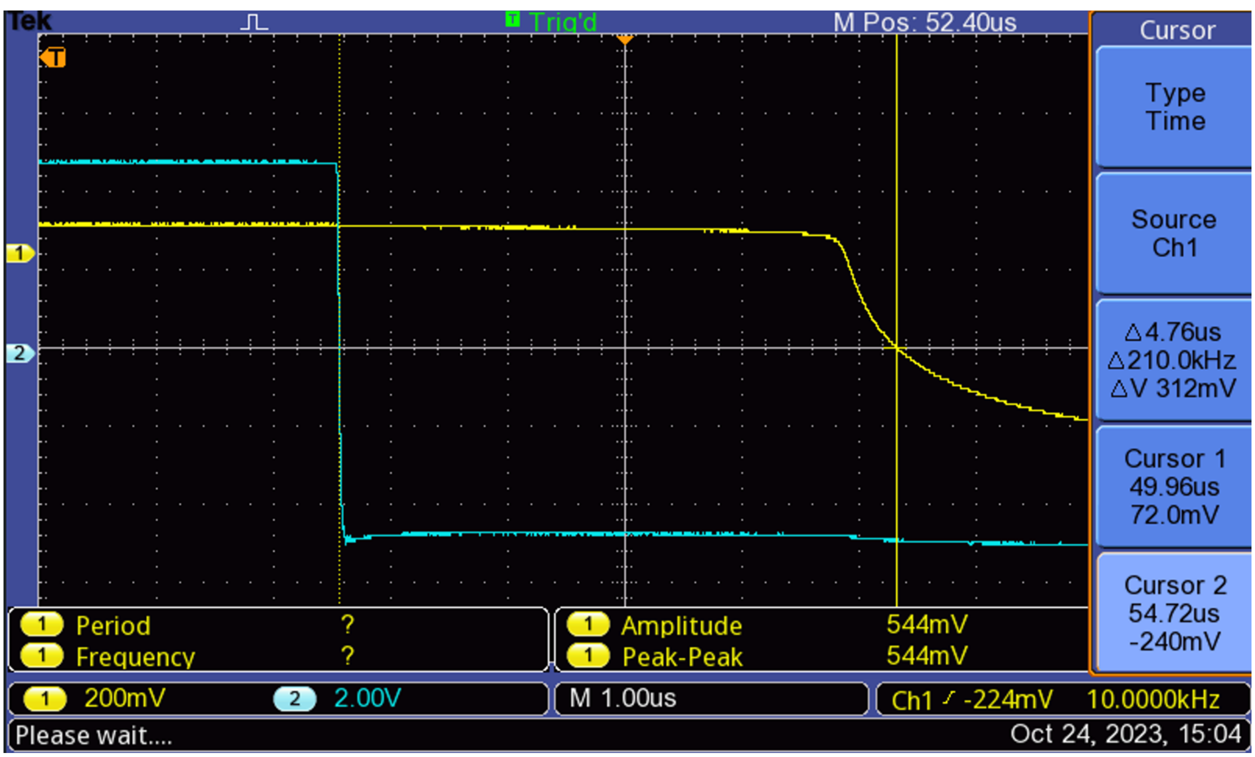
1. Measure t_d and t_s for the 1N4001 rectifier diode
2. Replace the 1N4001 rectifier diode by a 1N4148 signal diode. Repeat the t_d and t_s measurement.

Results

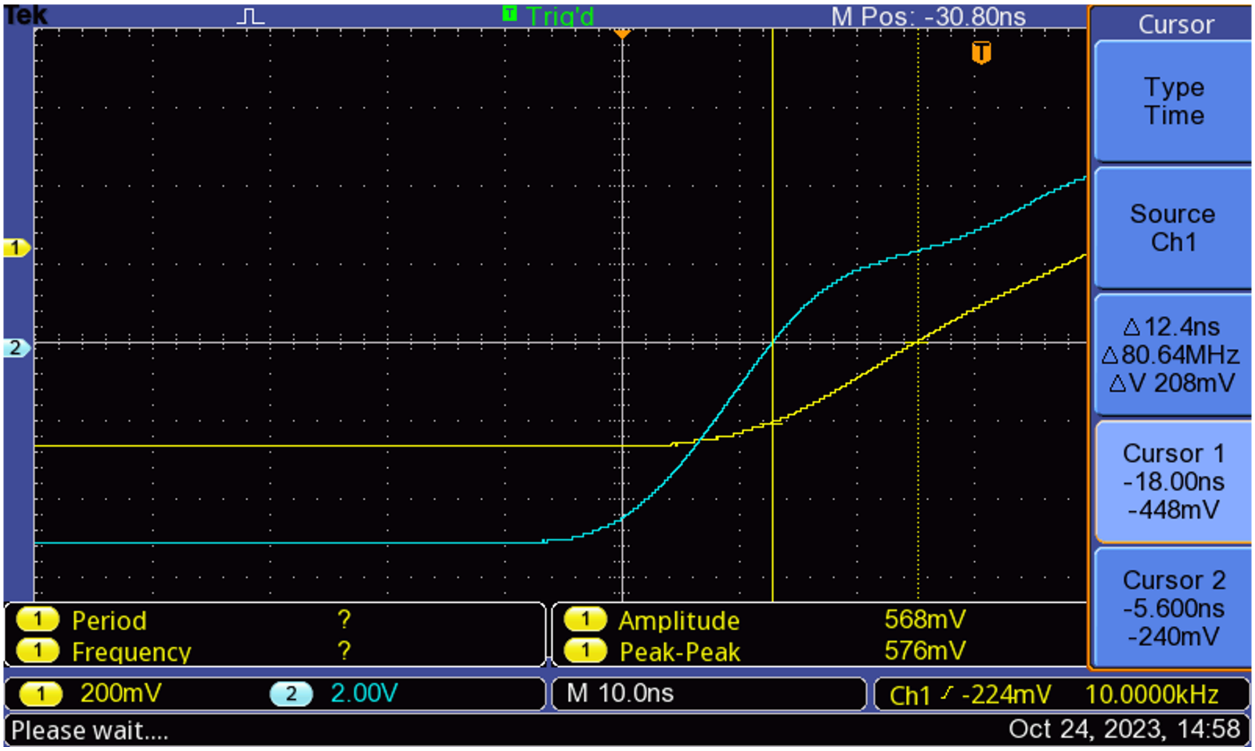


Rising Edge:

Falling Edge:



Rising Edge with 1N4148 signal diode:

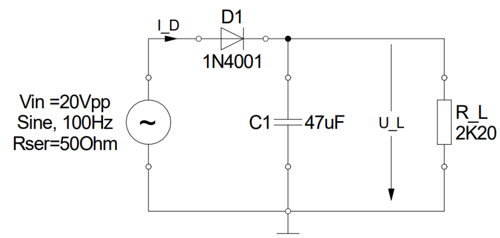


Falling Edge with 1N4148 signal diode:

Part 2 - Rectifier

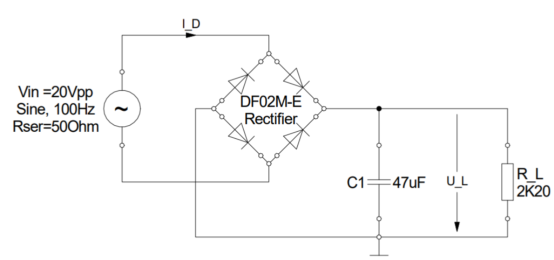
Experimental Setup and Procedure

1. Half-wave rectifier



   a. Remove C_1 and display and measure the peak voltage of V_{in} and V_L. Take a hard copy of the signals together with the measurements.
   b. Insert C_1 and display and measure the peak voltage of V_{in} and V_L. Take a hard copy of the signals together with the measurements.
   c. Zoom into the ripple voltage on top of V_L. Measure the peak-to-peak voltage of the ripple. Take a hard copy of the signal together with the measurements.

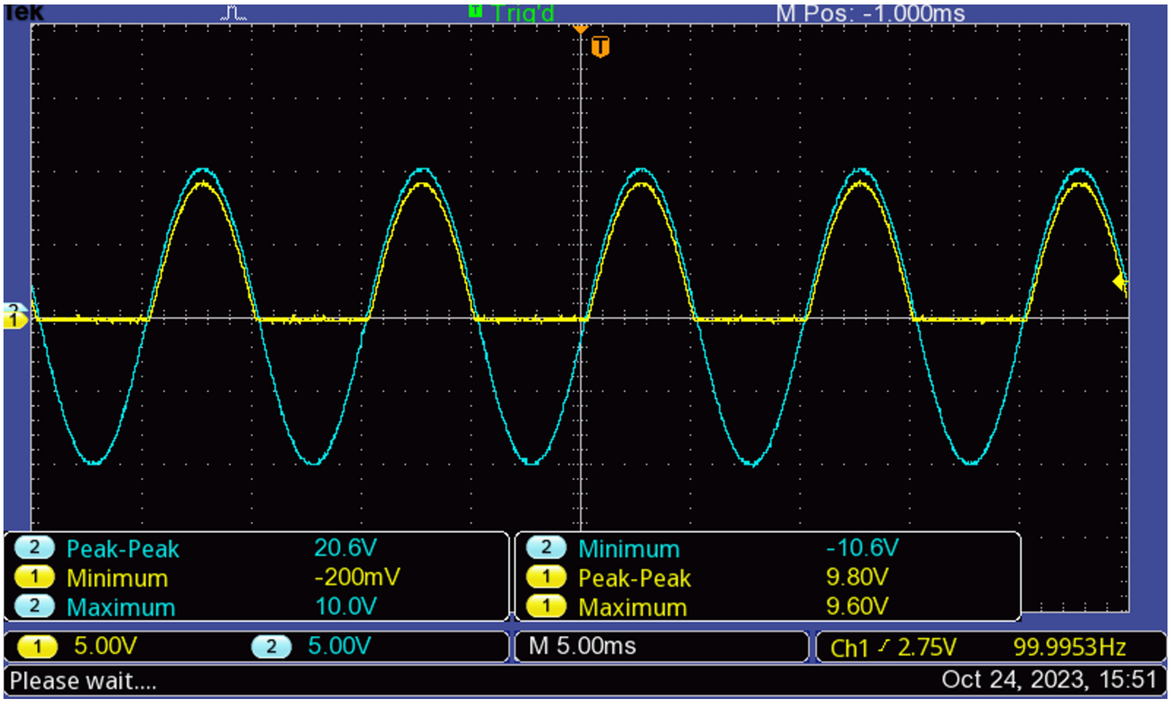
2. Full-wave Rectifier



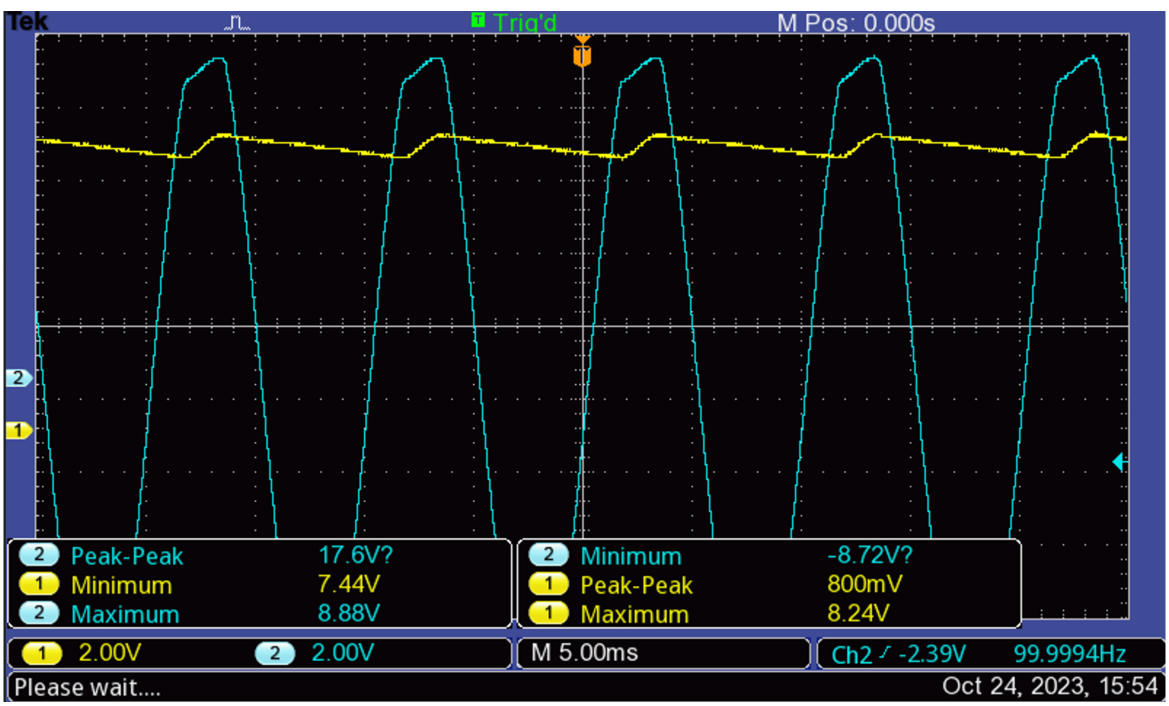
   a. Remove C_1 and display and measure the peak voltage of V_{in} and V_L. Take a hard copy of the signals together with the measurements.
   b. Insert C_1 and display and measure the peak voltage of V_{in} and V_L. Take a hard copy of the signals together with the measurements.
   c. Zoom into the ripple voltage on top of V_L. Measure the peak-to-peak voltage of the ripple. Take a hard copy of the signal together with the measurements.

Results

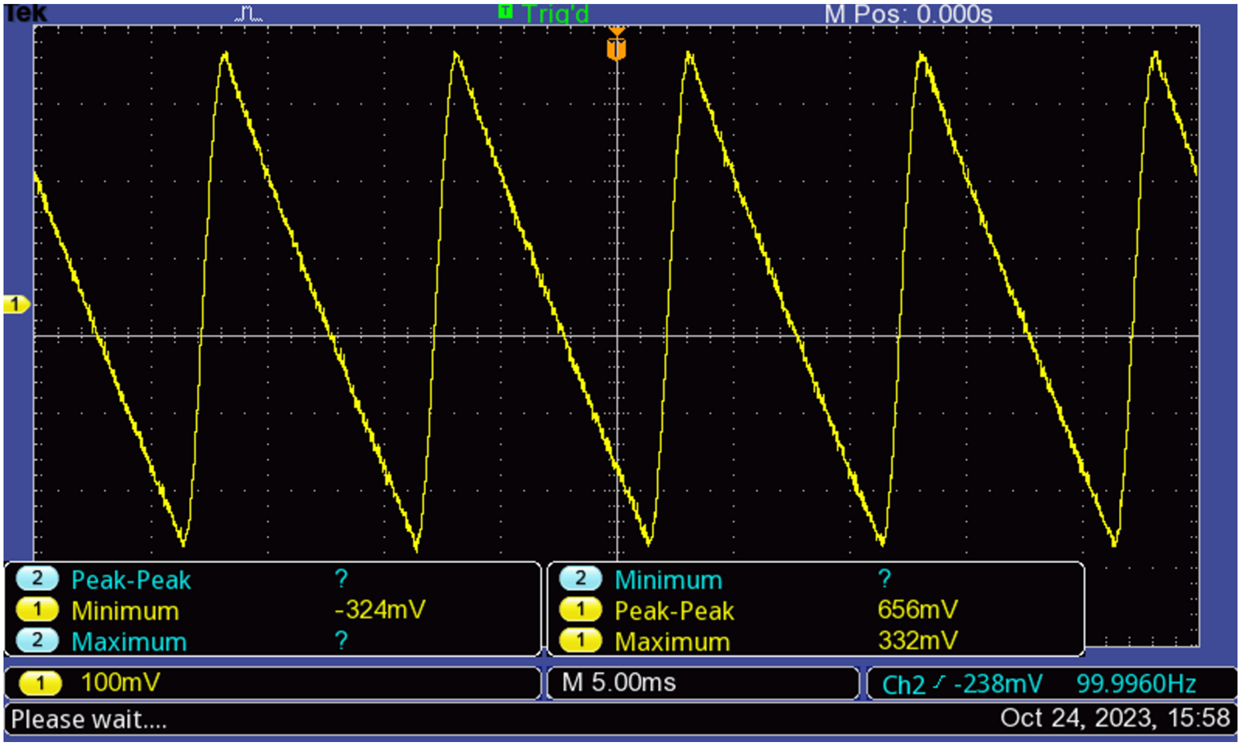
Half-wave rectifier, hard copy with C_1 removed:



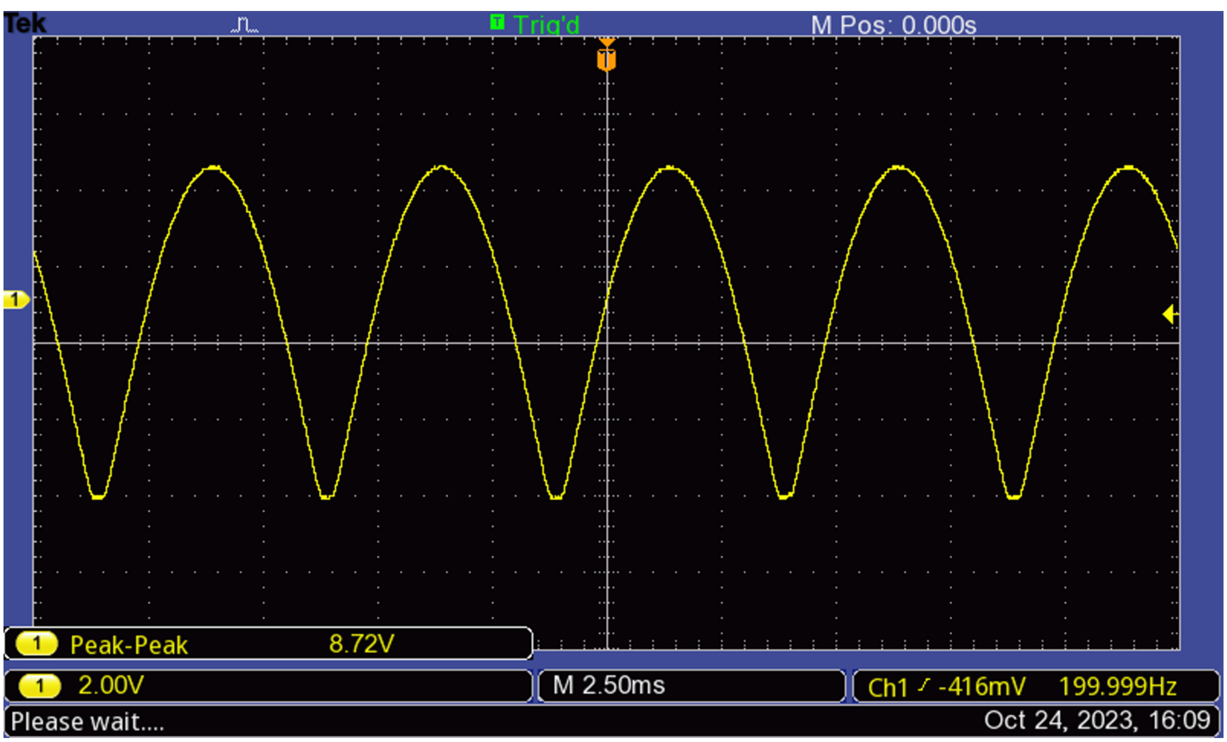
Half-wave rectifier, hard copy with C_1 inserted:



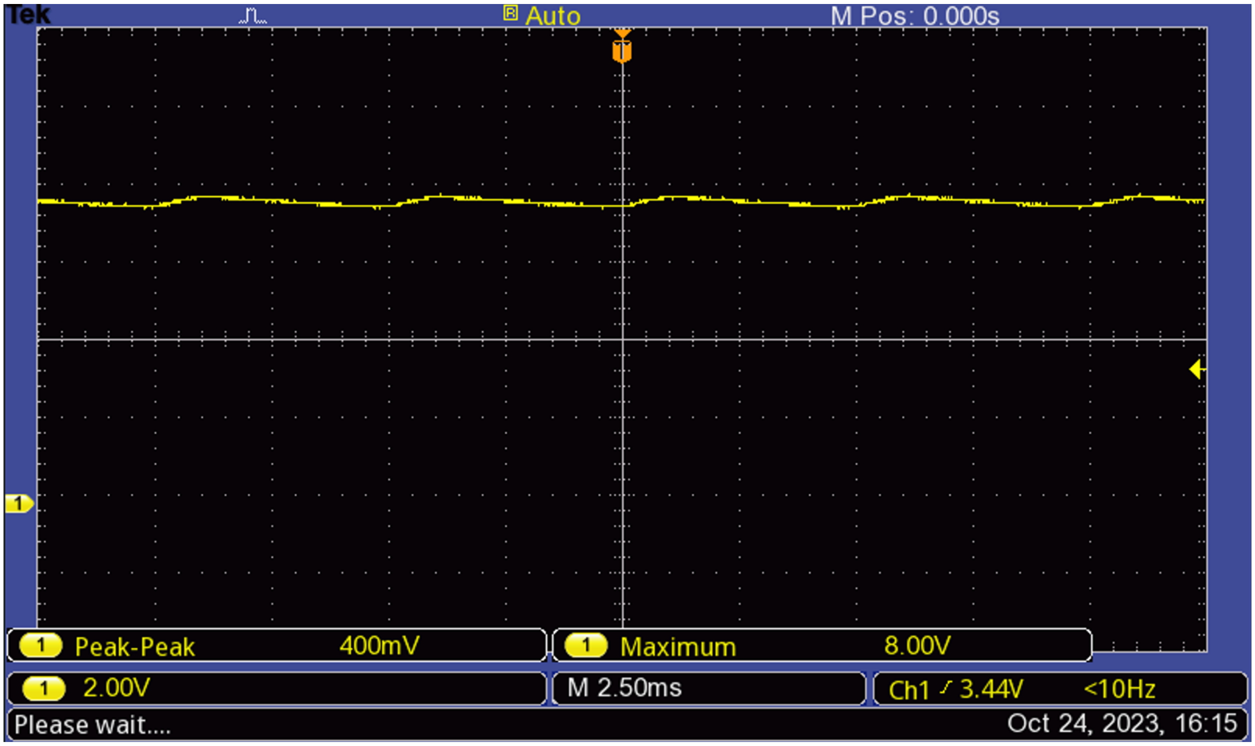
Half-wave rectifier, hard copy of ripple voltage:



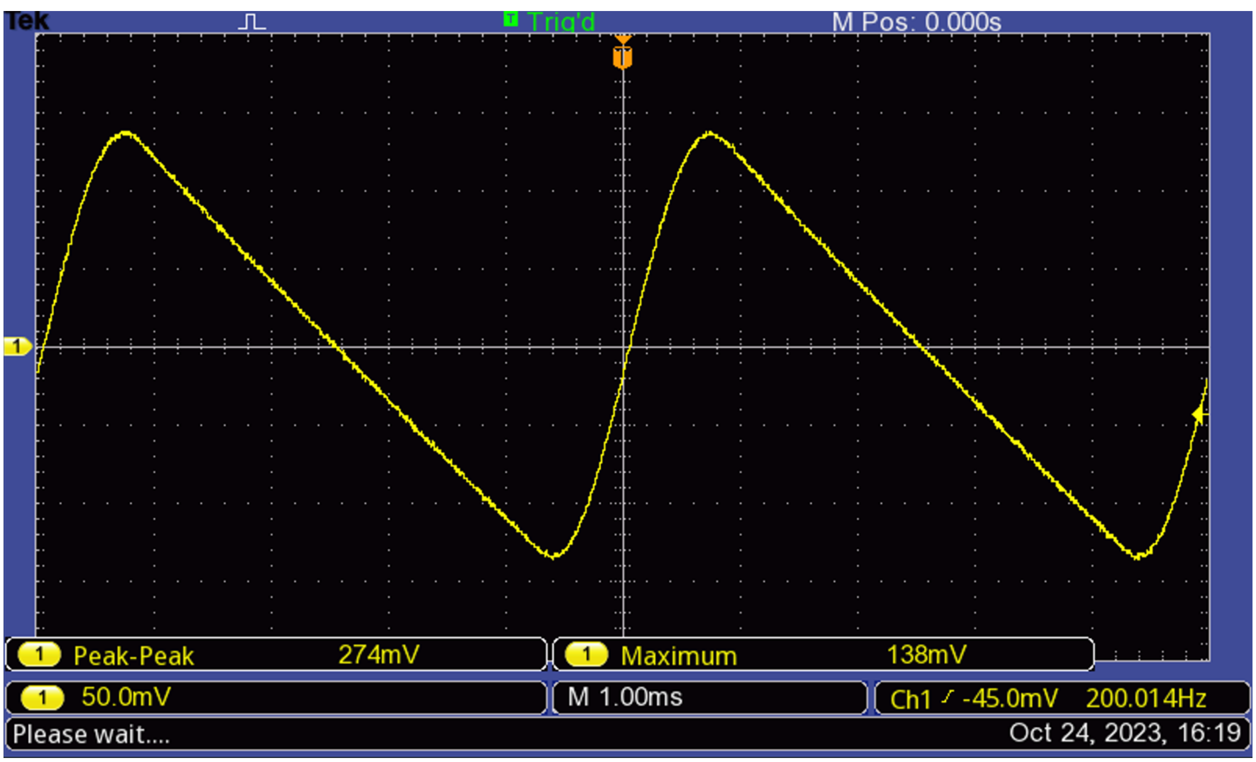
Full-wave rectifier, hard copy with C_1 removed:



Full-wave rectifier, hard copy with C_1 inserted:



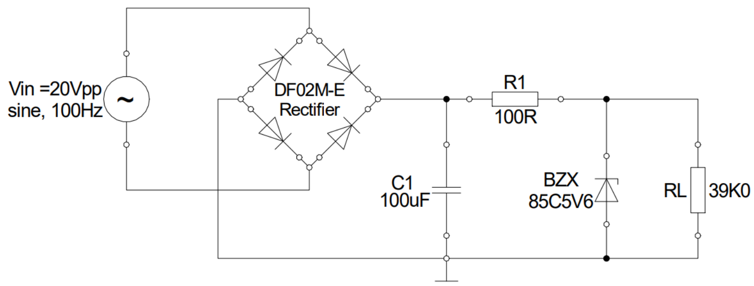
Full-wave rectifier, hard copy of ripple voltage:



Part 3 - Zener Diode

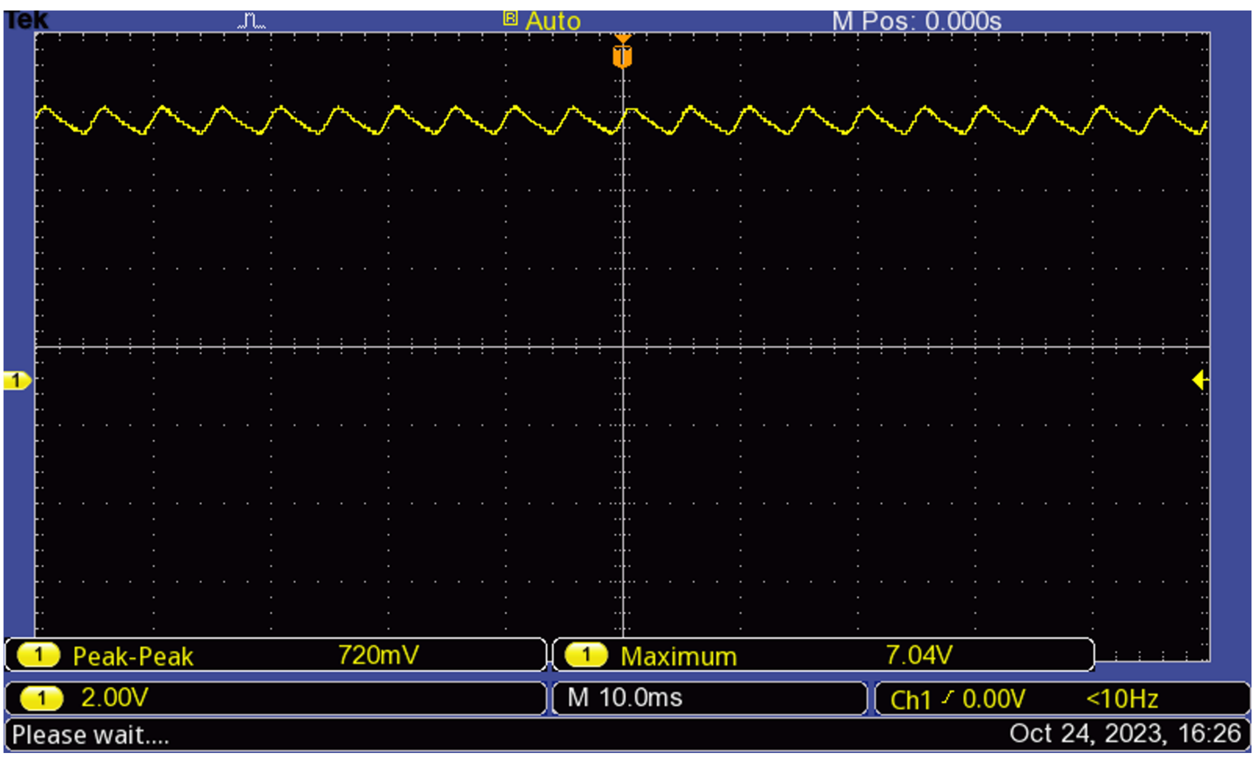
Experimental Setup and Procedure

Implement the following circuit. Measure DC and ripple voltage at C_1, the output DC voltage and the ripple across the load resistor R_L. Take a hard copies of the signals together with the measurements.

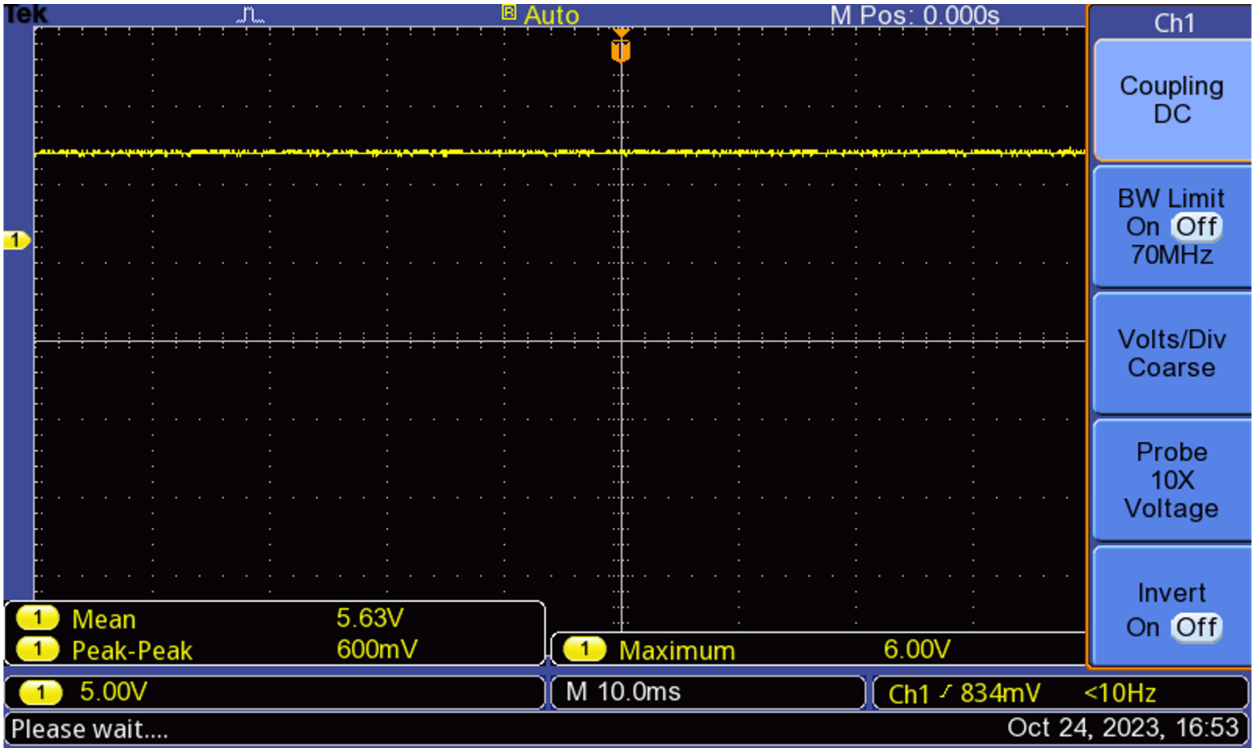


Results

Ripple voltage at C_1:



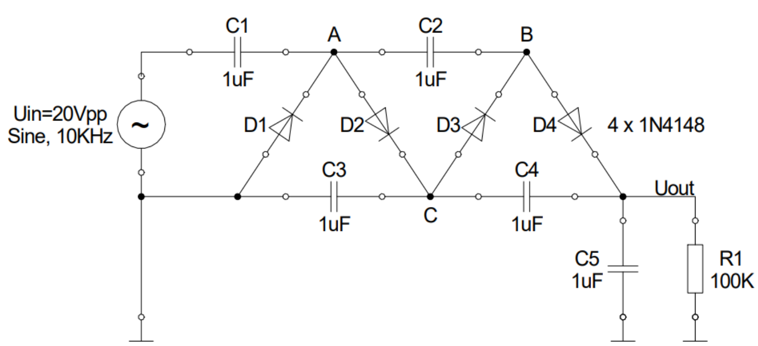
DC Output Voltage:



We forgot to take a picture of the Ripple Voltage at R_L

Part 4 - Voltage Multiplier

Experimental Setup and Procedure



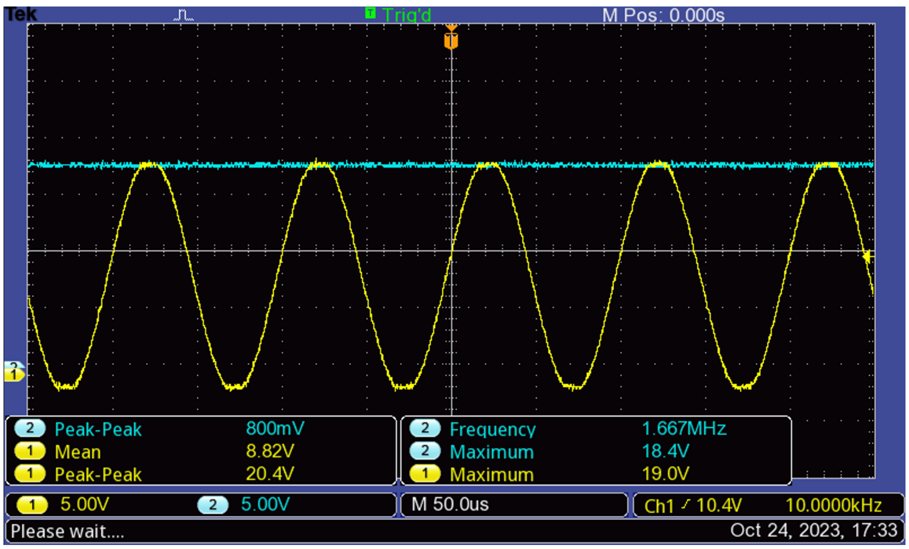
1. Use the oscilloscope to measure…
    a. the voltage at ’A’ and ’C’. Take a hardcopy with both signals together with the measurements.

b. the voltage at 'B' and 'U_{out}'. Take a hardcopy with both signals together with the measurements.

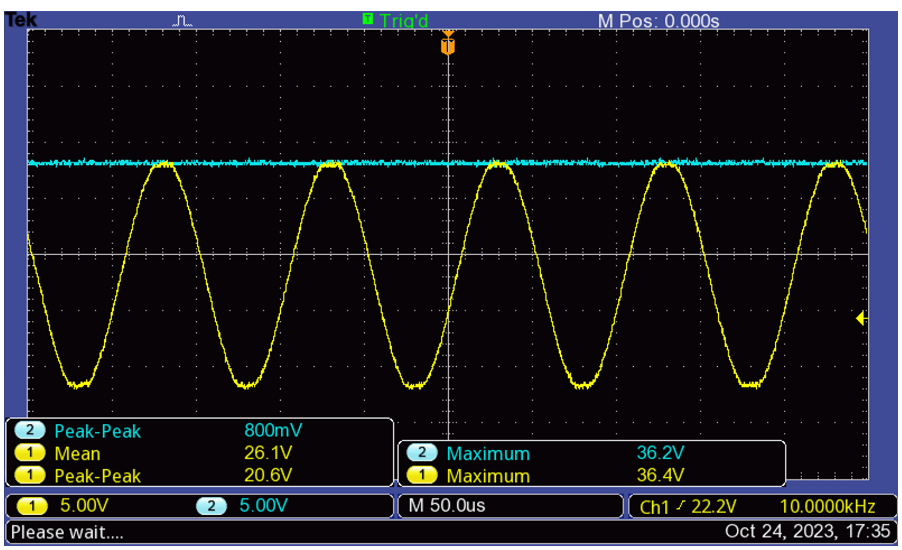
2. Measure the ripple voltage at 'U_{out}'. Take a hardcopy of the signal together with the measurement.
3. Measure and record the voltages at 'C' and 'Uout' using a multimeter.

Results

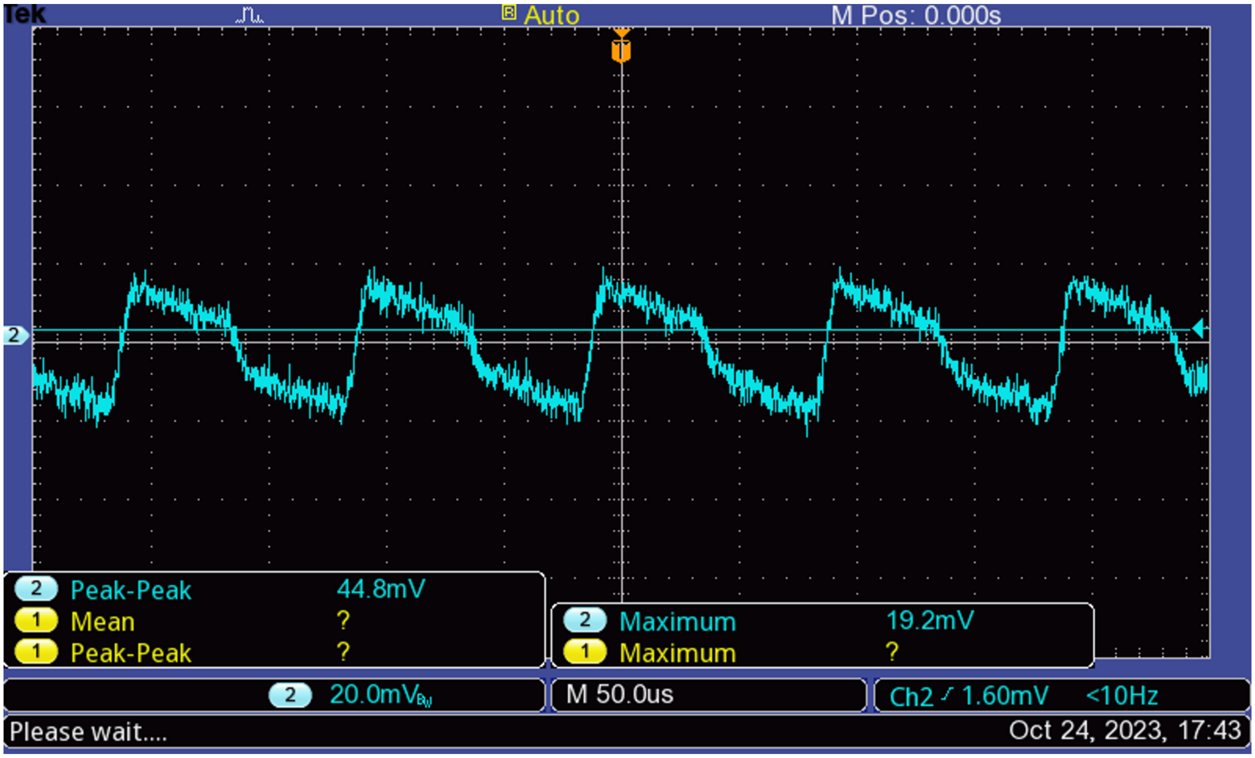
Voltage at A and C:



Voltage at B and U_{out}:



Ripple Voltage at U_{out}:



Using the multimeter, we got V_{out} = 35.487V and V_C = 17.749V

Evaluation

Problem 1 - Diode Switching Characteristic

1. **Compare the two storage times. What is the reason why the diode needs that long time to switch off?**

From the experimental findings, it is evident that the 1N4148 demonstrates a significantly smaller storage time compared to the 1N4001.

During state transitions, the diode must discharge any stored charges before manifesting characteristics related to the allowance or blocking of current flow. This requirement stems from the fact that the charge carriers within the diode necessitate a certain duration to respond to external changes and traverse the PN junction. Consequently, the diode exhibits a continuation of conduction for a period even after external conditions shift to reverse bias, or it remains non-conductive for a duration even after the external conditions switch to forward bias. This leads to the observed outcome that the diode experiences an extended switch-off time.

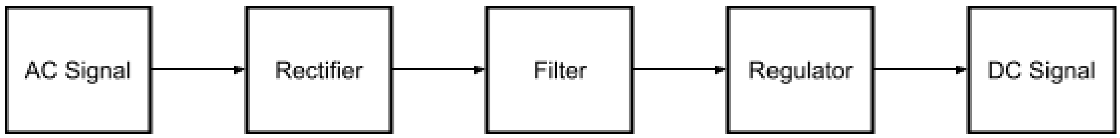
2. **What are the consequences of using these diodes in different applications? Think of the AM demodulation experiment when using several 100KHZ!**

Given its substantial storage time, it is evident that 1N4001 is not well-suited for processes like AM modulation of high-frequency signals, particularly those in the range of several hundred kilohertz. The extended storage time poses a risk of information loss and signal distortion, as the diode takes a considerable amount of time to switch between states during forward or reverse bias, making it unable to keep pace with the rapid fluctuations in the signal.

In contrast, 1N4148 proves more suitable for such applications than 1N4001. Its shorter storage time enables effective handling of high-frequency signals during AM modulation, minimizing the likelihood of information loss.

Problem 2 - Rectifier

1. **Draw a schematic diagram showing the building blocks of a DC power supply and explain the needs of each building block.**



The AC signal, sourced from a signal generator, undergoes rectification in our circuit using diode networks, transforming it into a unidirectional form. However, the rectified output exhibits significant fluctuations. To address this, a filter, employing a capacitor parallel to the load, smoothens the signal by providing power during periods when the input falls below the capacitor voltage. A regulator, featuring a Zener diode, ensures a consistent voltage and current at the output, regardless of variations in the input voltage or current. The ultimate output of the circuit is the DC signal, typically measured across the load.

2. **Compare the measured values of the peak-to-peak ripple voltages with the prelab values from simulation and calculation. Discuss the differences**

All numbers in mV	Measured Value	Simulated Value	Calculated Value
Half-Wave Rectifier	656	614.44	591.61
Full-Wave Rectifier	274	263.82	233.30

The table reveals a degree of correlation among the simulated, measured, and calculated values, indicating mutual confirmation. The observed discrepancy in the measured value is evident and can be attributed to factors such as the oscilloscope's resolution, precision errors during measurements using the cursor, and errors associated with the signal generator. Additionally, non-ideal components like diodes and capacitors may contribute to the error due to internal resistance or the time required for transitioning between states. It is crucial to note that the formula in the manual serves as an approximation for the ripple voltage and does not furnish the precise value.

Problem 3 - Zener Diode

Calculate the approximate current through the Z-diode!

We know $I_{RL} = \frac{V_{RL}}{R_L}$ and $I_{R1} = \frac{V_{R1}}{R_1}$, and we got V_{RL}=5.63V, V_{C1}=6.71V, V_{R1}=6.71-5.63=1.08V

Then by KCL,

$$I_Z = I_{R1} - I_{RL} = \frac{V_{R1}}{R_1} - \frac{V_{RL}}{R_L} = \frac{1.08}{100} - \frac{5.63}{39000} = 10.66mA$$

Problem 4 - Voltage Multiplier

1. **From which circuits in the Diode Application part of the handout this circuit is composed?**

The circuit is composed of a combination of the clamper circuit and rectifier circuits.

2. **Explain the function.**

Clamper circuits play a vital role in restoring DC levels in circuits following diverse filtering processes. The incorporation of a diode in the circuit rectifies AC voltage, enabling the smoothing and conversion of the signal into a DC voltage. The capacitor, functioning as a smoothing filter, ensures that the output closely resembles a DC voltage. Through various networks, these components work in harmony to convert a two-directional AC voltage into a unidirectional DC voltage, accompanied by a minor ripple residue from the AC signal. In the provided network, clampers are strategically utilized to introduce a DC voltage level to the signal without compromising its inherent shape. Subsequently, the signal undergoes rectification, culminating in a transformed and smoothed DC voltage, characterized by a slight ripple.

3. **What is the multiplication factor between input amplitude and output voltage? Compare the measured to the ideal one. Why is there a difference?**

There are four clampers, so the DC output should be 4 times the input amplitude.

Ideal Values:	V_{in} = 10V	V_{out} = 40V	Multiplication Factor: 4
Measure Values:	V_{in} = 10V	V_{out} = 36.4V	Multiplication Factor: 3.64

The diodes within this network necessitate a minimum operating voltage crucial for both individual diode functionality and the overall network operation. Each diode introduces a voltage drop, collectively leading to a reduction in the voltage across the load. Consequently, the measured output is lower than the expected ideal output, primarily due to these potential drops across the diodes.

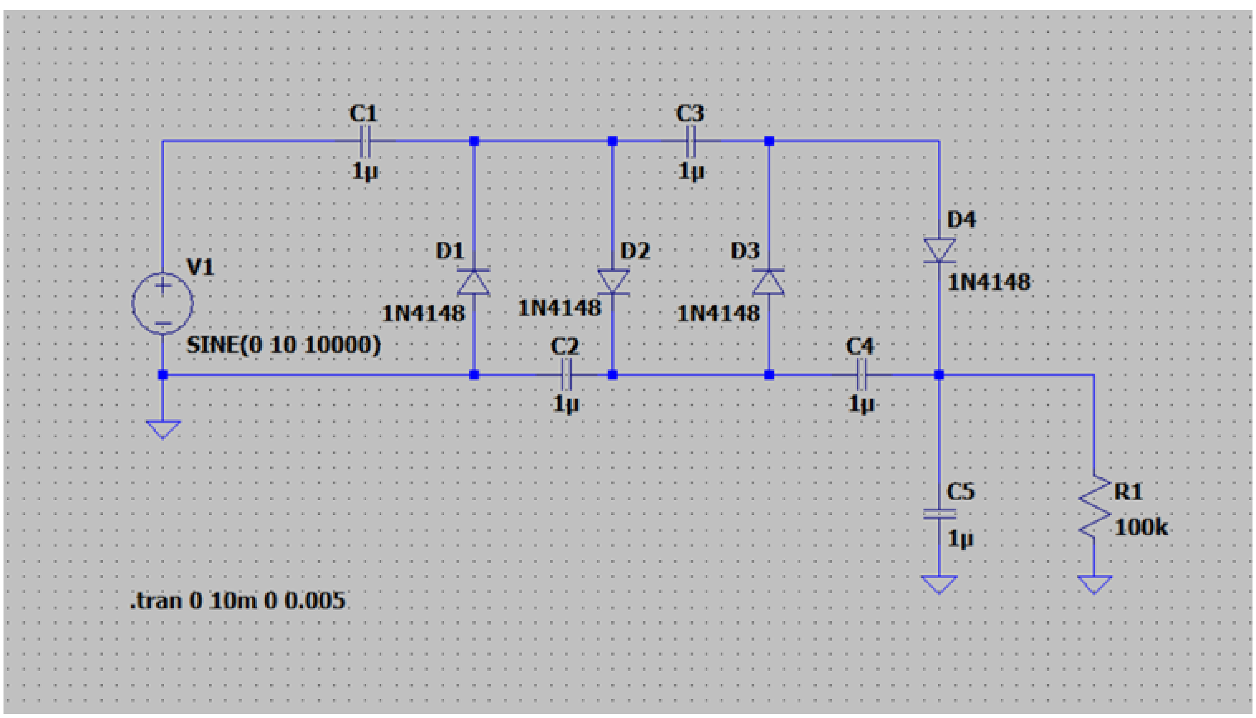
4. **For which maximum voltage each element has to be selected?**

The voltage at each element is twice the amplitude, therefore, at least two times the peak voltage is required. The maximum voltage at each element is V_{pp}.

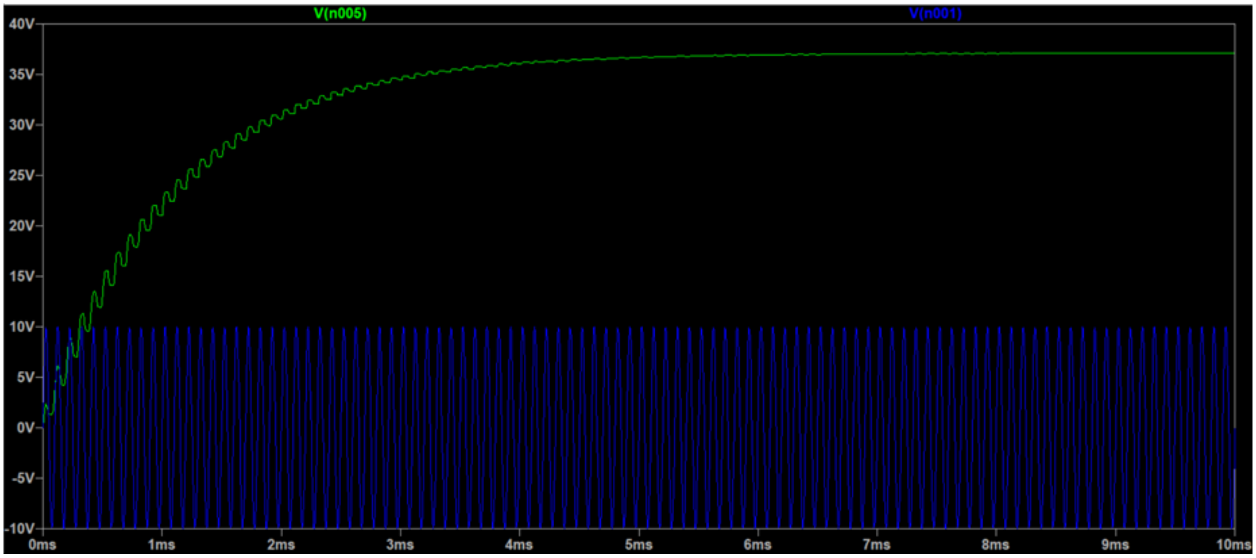
5. **What happens to U_{out} if the frequency of the input voltage is reduced to 100 Hz (Voltage & ripple!)? Explain in words!!! Show proof of your statement using PSpice!**

Reducing the frequency to 100Hz leads to a decrease in Uout. Higher frequencies result in more frequent charging of capacitors, indicating that circuits operating at higher frequencies exhibit a lower ripple compared to circuits functioning at 100Hz.

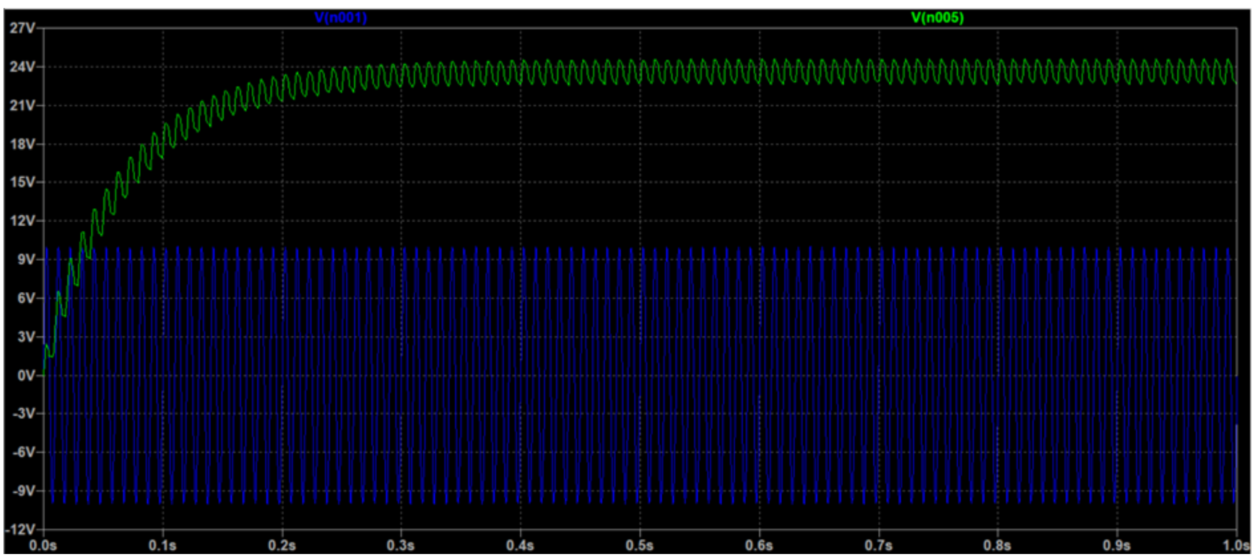
To prove the hypothesis, we simulate the following circuit:



At 10kHz:



At 100Hz:



As observed, the output voltage is lower at 100Hz than at 10kHz, and the ripple is smoother in the 10kHz circuit. Additionally, the output stabilizes much faster in the 10kHz circuit compared to the results obtained at 100Hz.

Conclusion

In this comprehensive experiment, our primary objective was to delve into the characteristics of diodes and their multifaceted applications across various circuit configurations, including an exploration of Zener diodes. The intricate study involved the integration of these diodes into diverse circuits such as rectifying circuits, clamper circuits, and voltage multipliers. Our initial focus was on scrutinizing two distinct diodes, revealing a significant difference in turn-off time, rendering one diode more suitable for certain circuits.

The subsequent phases of the experiment revolved around an in-depth analysis of half-wave and full-wave rectifier circuits, emphasizing the impact of capacitors on circuit behavior. Further exploration encompassed the influential role of Zener diodes in circuits and an examination of voltage multipliers—a combination of clampers and rectifiers.

Comparison among simulated, measured, and calculated values exposed discernible discrepancies attributed to instrumental error, non-ideal diode application, and challenges in value interpretation from simulations and the oscilloscope. Instances where approximations were employed were highlighted to simplify the analytical process.

During the prelab phase, meticulous simulation of various diode circuits using LTSpice facilitated a comprehensive understanding of their characteristics. The exploration began with a fundamental diode circuit, progressing to the study of half-wave and full-wave rectifiers, where the importance of capacitors in achieving a smoothing effect was evident. Noteworthy observations included the blocking of negative cycles by the half-wave rectifier and the inversion of these cycles by the full-wave rectifier, resulting in a smoother ripple output.

The lab implementation involved replicating prelab simulations, and the results obtained in both instances exhibited remarkable consistency. The addition of a regulator to the full-wave rectifier proved instrumental, delivering a significantly improved DC output by mitigating fluctuations across the load. The study of a voltage multiplier, formed by combining the clamper circuit and the rectifier circuit, further highlighted the influence of diodes on output voltage, showcasing distinctions between theoretical and experimental outcomes. Notably, simulations with varying input frequencies (100Hz and 10kHz) revealed considerable differences in output, with the 10kHz frequency yielding higher output voltage and smoother ripples.

In the evaluation phase, a nuanced examination of diode storage times underscored their practicality in different scenarios. The comparison of measured data from rectifier experiments with simulated and calculated data yielded aligned results, albeit with slight deviations. The assessment of Zener diode behavior and the voltage multiplier network further enriched our understanding. Simulations with different input frequencies provided insights into frequency-dependent variations in output characteristics.

In summary, this comprehensive approach, incorporating simulations, theoretical constructs, and experimental data, enabled a profound exploration of diode characteristics, configurations, and applications. The study illuminated the intricate interplay of diodes with other electrical components, providing valuable insights into the deviation of real-world behavior from theoretical expectations. This comprehensive understanding equips us to identify error sources and anticipate outcomes in experimental scenarios.

References

Pagel, Uwe. *CO-526-B Electronics Lab Manual*. 2023.