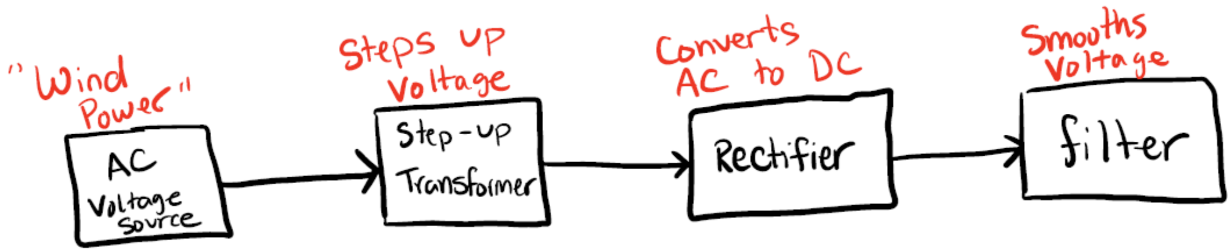
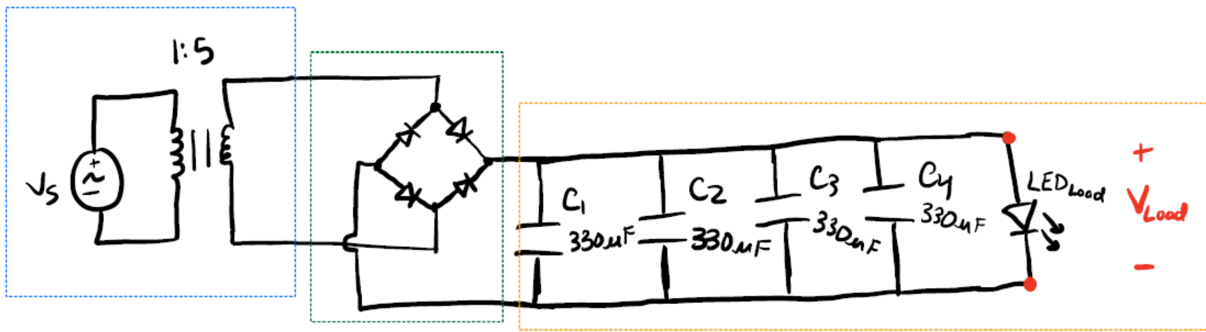
Proof of Concepts Milestone 3

Josh Suber, Ethan Wong and Kevin Raj

Block Diagram:



Labeled Circuit Diagram:

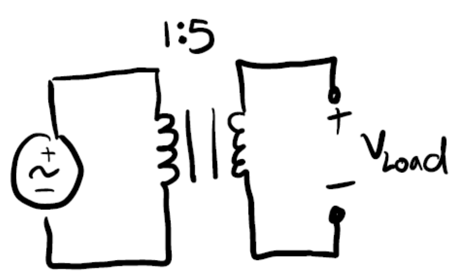


Circuit Specifics:

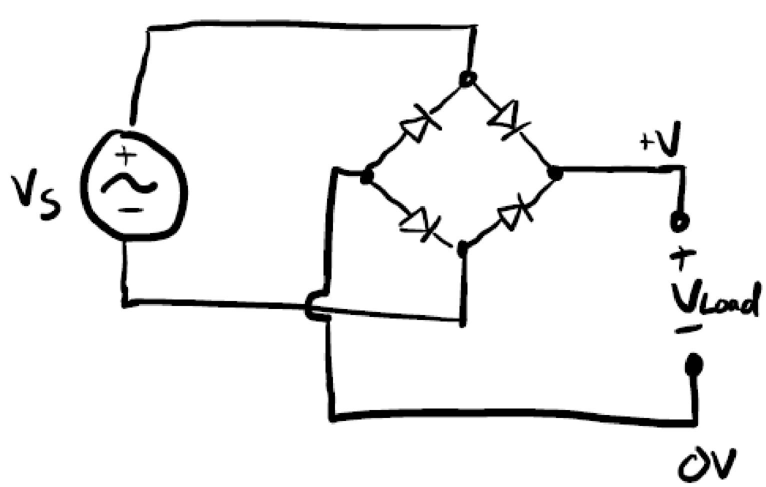
- Vs is an AC voltage source with an amplitude of 5V and a frequency of 40k Hz.
- The blue is a step-up transformer with 6 loops in the primary loop and 30 in the secondary loop giving it a 1:5 ratio.
- The green is a rectifier which takes our stepped-up AC source and converts that to DC.
- The orange is then a filter that will smooth out the rectifier's output.
- LED_{load} is the output we would combine with the output of that the solar panels generate.
- This is all to simulate how we would convert and combine the AC voltage we would get from wind turbines and combine it with our DC voltage from our solar panels.

Components:

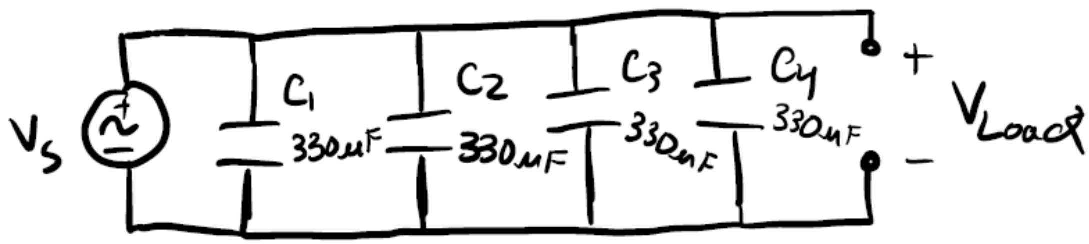
Transformer:



Rectifier:



Filter:



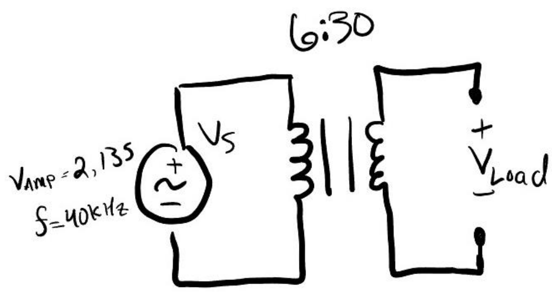
Concept 1: Transformer Analysis (ideal and non-ideal)

Description :

Inductors are used to set up and step-down voltages. For our use case we used the inductor to step up the voltage. Because we are trying to simulate the process of rectifying an ac source, we need to use diodes that only allow current to pass in one direction. This converts the AC source to a DC source as only positive voltage can now flow pass the rectifier. The limitations of diodes is that they have a turn on voltage that can prevent current and voltage to pass if those specifications are not met. By using a transformer we are able to increase our voltage output and increase the turn on voltage giving us more usable power.

Analysis :

Ideal transformer Analysis

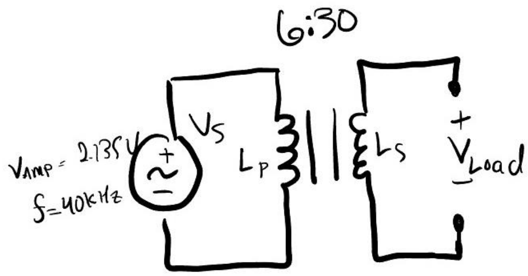


$$\frac{V_{Load}}{V_{Amp}} = \frac{N_s}{N_p} \longrightarrow \begin{array}{l} V_{AMP} = 5V \\ N_s = 30 \text{ loops} \\ N_p = 6 \text{ loops} \end{array}$$

$$V_{Load} = \frac{N_s}{N_p} \cdot V_{AMP} = \frac{30}{6} \cdot 2.135V = 10.675V$$

$$V_{Load} = 10.675V$$

Non-ideal transformer analysis:



- $V_{Load} = \frac{N_S}{N_P} \cdot V_{AMP} \cdot n \rightarrow n$ is the efficiency of the transformer which accounts for loss

- For many practical transformers at 40kHz efficiency can range between 90% to 98% depending on quality and design specifics

Low end ($n = 0.9$):

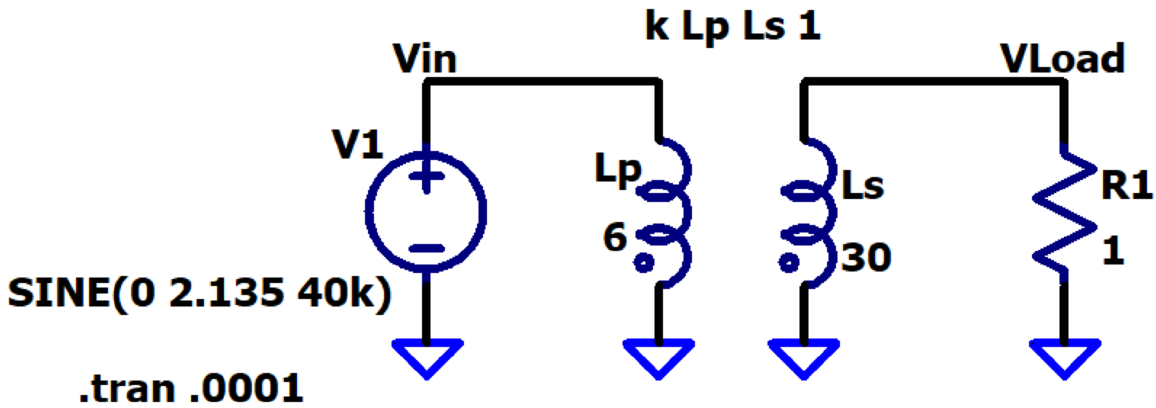
$V_{Load} = \frac{30}{6} \cdot 2.135 \cdot 0.9 = 9.61V$ $\Rightarrow$ **9.6V - 10.5V**

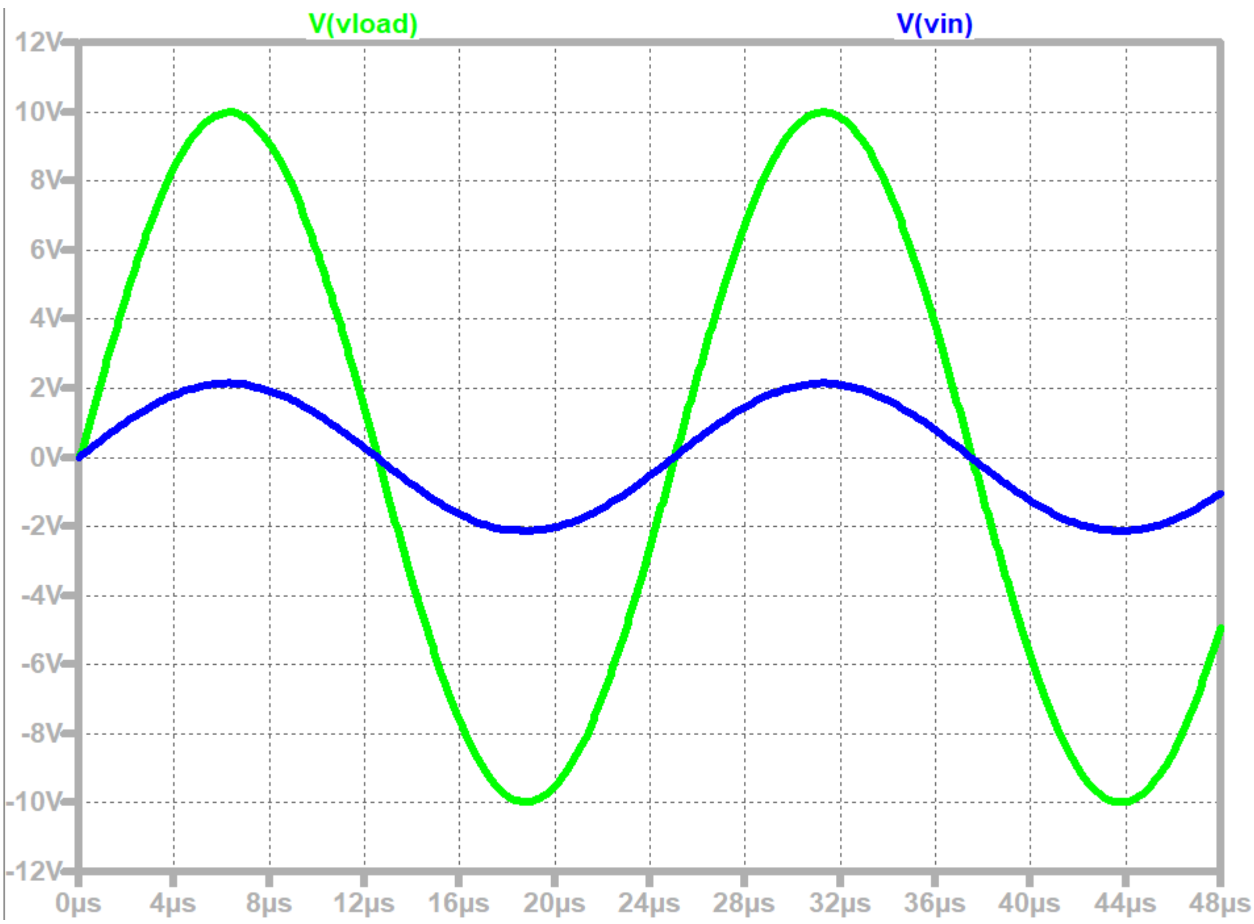
High end ($n = 0.98$):

$V_{Load} = \frac{30}{6} \cdot 2.135 \cdot 0.98 = 10.46$

According to the analysis we should see a voltage increase of around 5 times the input voltage. In this case our 2.135V input should be boosted to a voltage of 10.675V. However, this is for an ideal transformer which is what we will not be dealing with in our measurements in the physical circuit. If we are dealing with an efficiency of 90-98% which is what a practical transformer should produce at 40k Hz (which is what our input signal is) we should expect to see a voltage ranging from 9.6-10.5V.

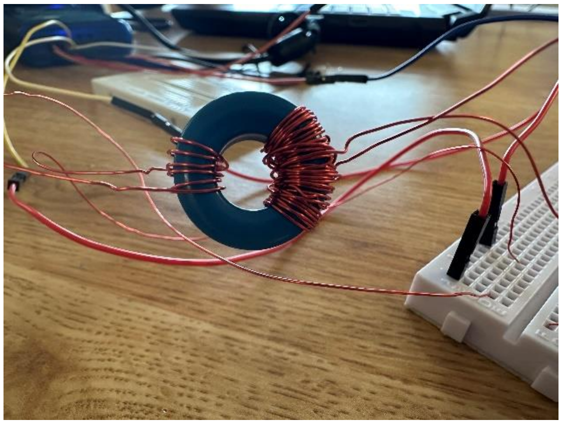
Simulation :



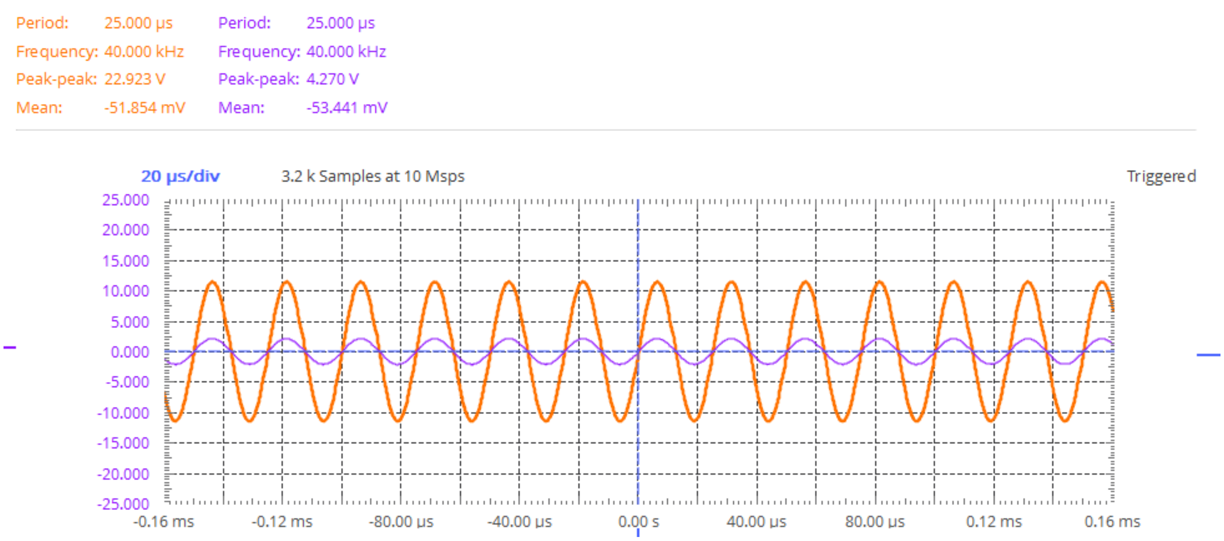


Using LTspice we are able to demonstrate that properties of this inductor. As you can see our primary inductor Lp in modeling an inductor with 6 loops where our secondary inductor Ls is modeling an inductor with 30 loops. From the simulation You can see we boosted our 2.135V input source to just about 10V which is what our calculations predicted we would see.

Experimental Data :



This is the transformer with 6 loops on the primary side and 30 on the secondary side. It is made with a steal core and 26 gauge magnet wire.



Purple is the input voltage and the orange is the output voltage from the transformer.
The output has an amplitude of about 11.5V and the input has an amplitude of 2.135V. This falls inline with what we expected to see from our calculations and simulation.

Results:

The alignment between theoretical predictions, simulation results, and experimental data in Concept 1 revolves around the efficiency of the transformer and the actual output voltage obtained. Here's how they compare and potential reasons for discrepancies:

1. **Theoretical Predictions:** Theoretically, the output voltage was expected to be about 5 times the input voltage (2.135V x 5 = 10.675V), assuming an ideal transformer.
2. **Simulation Results:** The simulation using LTspice showed a boosted output of approximately 10V from an input of 2.135V. This is slightly below the ideal theoretical prediction of 10.675V but still

within a close range, indicating that the simulation accounted for some non-ideal factors of the transformer, possibly the inherent inefficiencies in the transformer design such as resistance in the windings or magnetic losses.

3. **Experimental Data:** The actual experimental results showed an output voltage amplitude of about 11.5V, which is higher than both the theoretical prediction for an ideal scenario and the simulation results. This deviation suggests that the transformer performed better than expected under the specific experimental conditions.

Potential Reasons for Discrepancies:

- **Efficiency and Losses:** Transformers are not 100% efficient due to losses like core losses (hysteresis and eddy currents) and copper losses (resistance of the windings). The efficiency can vary depending on the frequency of operation and the quality of the core material. An efficiency of 90-98% was expected in practical scenarios at 40 kHz, which could explain the lower than theoretical output voltage in the simulation.
- **Load Conditions:** The load connected to the transformer during experiments can influence the voltage drop across the transformer. If the experimental setup had less load or lower resistance compared to what was assumed in the theoretical calculations, this could result in a higher output voltage.
- **Measurement Errors:** Variations in measurement tools or methods, including the calibration of voltage measuring equipment and the precision of input voltage settings, can also contribute to discrepancies between theoretical, simulated, and experimental results.
- **Physical Properties of Components:** Differences in the physical properties of the components used in the experiment versus those assumed in the simulation and theory (e.g., variations in wire gauge, core material quality) could impact the magnetic efficiency and resistance, altering the output voltage.

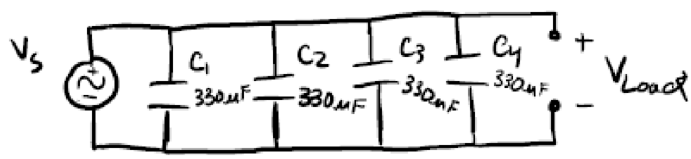
Concept 2: Filter Analysis

Description :

The aim of Concept 2 is to analyze the performance and effectiveness of filters in manipulating signal properties to meet specific needs. This includes attenuation or amplification of frequencies to isolate or eliminate unwanted noise and enhance desired signal components. In this we will be analyzing transfer functions, bode plots, and db roll off. In our physical circuit we are using the filter in tandem with a rectifier to eliminate noise and create a constant DC voltage source from an AC input.

Analysis :

Filter analysis:



$C_{tot} = 4(330\,\mu F) = 1320\,\mu F$

$$H(s) = \frac{1}{sC_{tot}} = \frac{1}{s(1320 \times 10^{-6})}$$

$$H(s) = \frac{1}{s(1320 \times 10^{-6})}$$

Bode Plot:

- The magnitude response shows a decreasing trend as frequency increases, indicative of a typical low-pass filter.

- The phase response remains constant at -90° across all frequencies, which is characteristic of a pure capacitive load.

Poles and zeros:

Zeros: the zeros of the transfer function occurs where the numerator becomes zero. Since the numerator of H(S) is a constant (1) there are no zeros in the transfer function.

Poles: the poles occur when the denominator of H(S) is zero.

$$H(S) = \frac{1}{(1320\times10^{-6})s} \Rightarrow (1320\times10^{-6})s = 0$$

↳ Poles: $s=0$

This pole at the origin reflects the behavior typical of a capacitive elements in the frequency domain, where the response magnitude increases as the frequency approaches zero, emphasizing the low-pass characteristic of the circuit. There are no finite zeros in this transfer function, indicating no specific frequency at which the output is forced to zero by the function itself.

Cutoff frequency (f_c):

$$|H(j\omega)| = \left|\frac{1}{RCj\omega+1}\right| = \frac{1}{\sqrt{(RC\omega)^2+1}}$$

$$\frac{1}{\sqrt{(RC\omega)^2+1}} = \frac{1}{\sqrt{2}} \rightarrow \sqrt{(RC\omega)^2+1} = \sqrt{2}$$

$$(RC\omega)^2+1=2 \rightarrow (RC\omega)^2 = 1 \rightarrow \omega = \frac{1}{RC}$$

Assuming $R = 1\Omega$ and $C = 1320\times10^{-6}$ F

$$\omega_c = \frac{1}{RC} = \frac{1}{1320\times10^{-6}} = 757.576$$

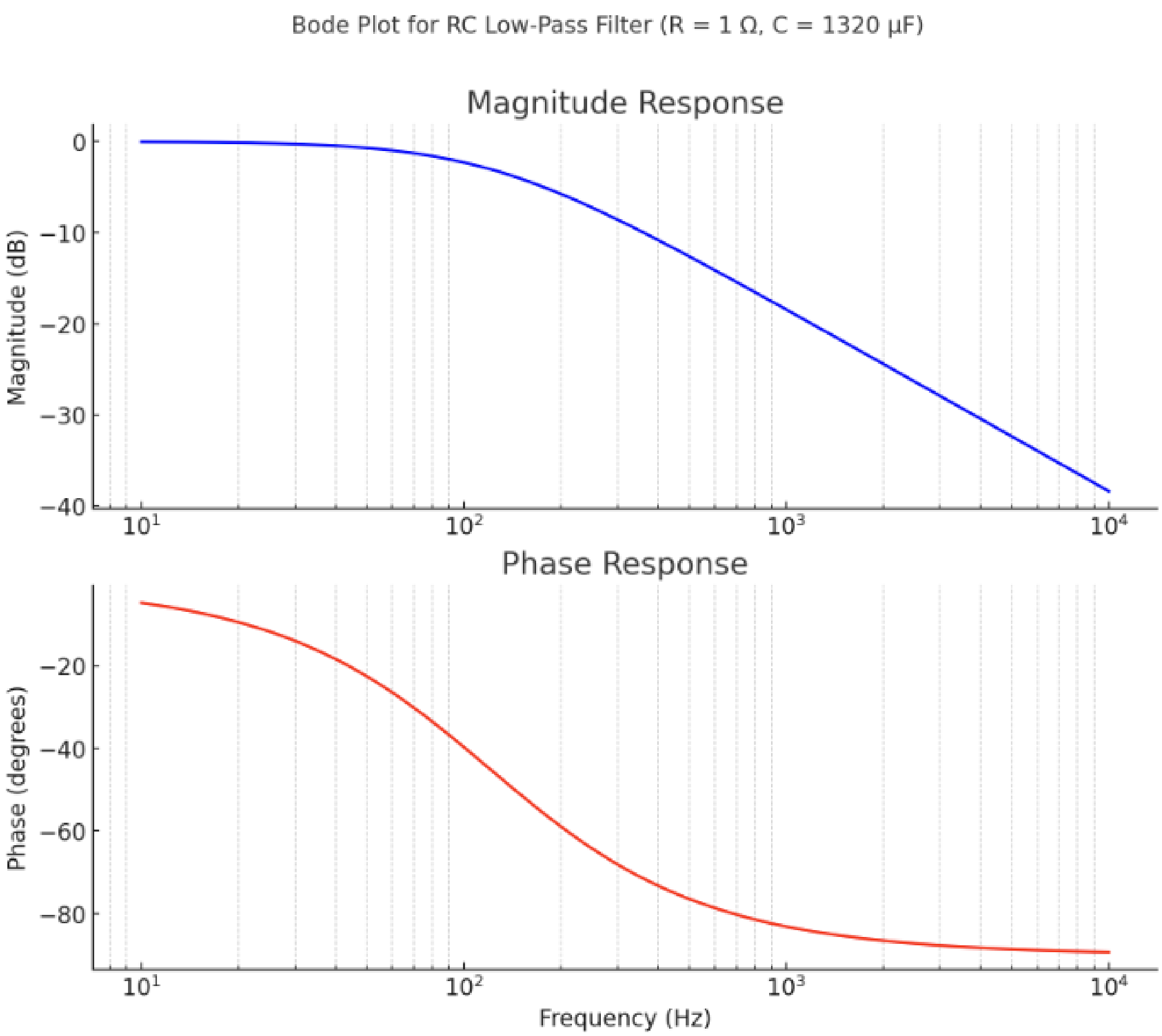
$$f_c = \frac{\omega_c}{2\pi} = \frac{757.576}{2\pi} = 120.57 \text{ Hz}$$

$$\boxed{f_c = 120.57 \text{ Hz}}$$

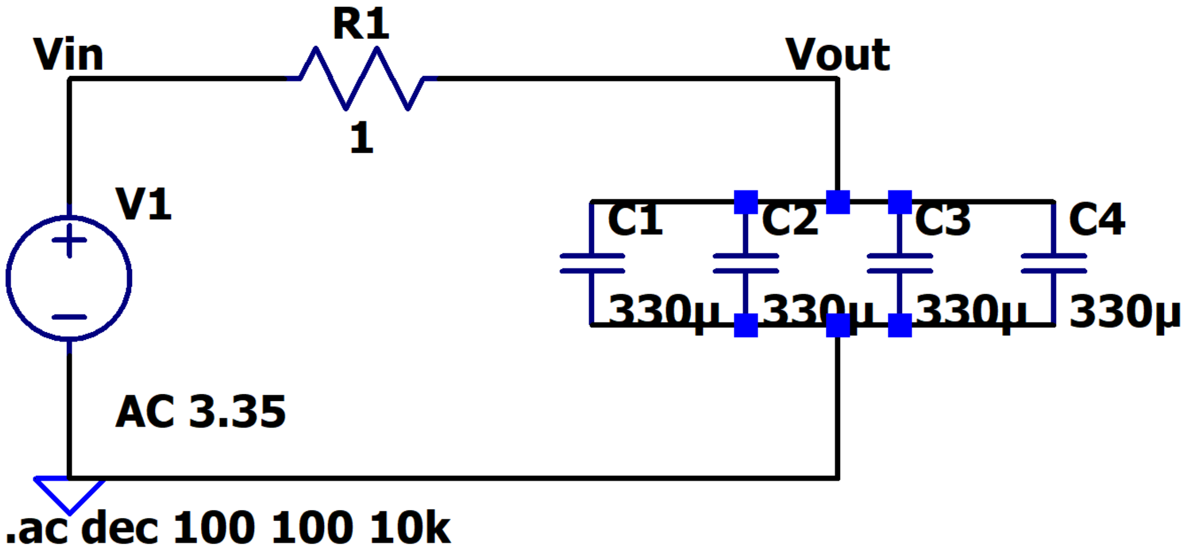
This value represents the frequency at which the magnitude of the transfer function drops to -3 dB, indicating a point where the capacitive reactance equals the resistance, thus attenuating the signal's power by half at this frequency.

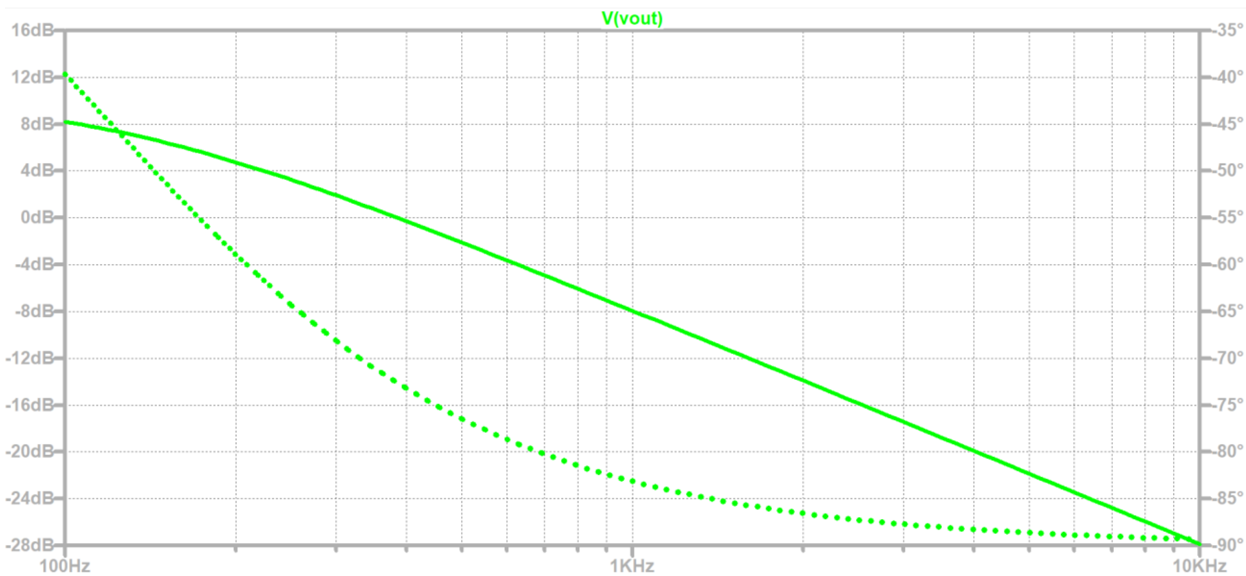
Roll off in dB

- The rolloff rate for a first order low-pass filter is 20 dB/decade. This means that for each tenfold increase in frequency beyond the cutoff frequency, the signal's power level decreases by 20 dB.



Simulation :





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Frequency Response Graph:

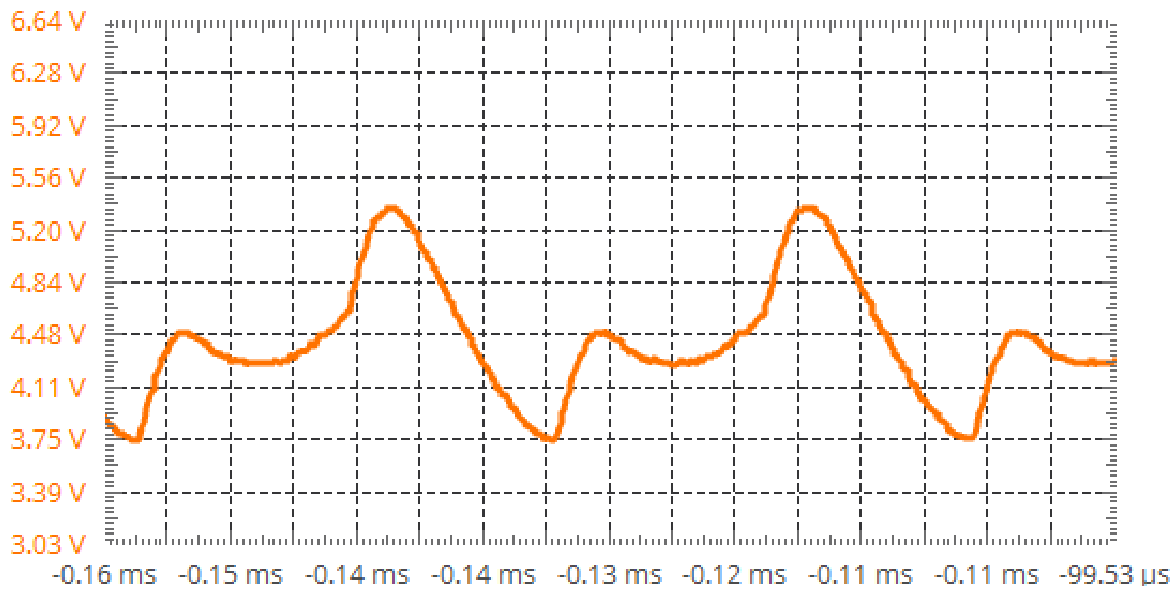
- The frequency response graph plots the output voltage (Vout) gain in decibels (dB) against frequency on a logarithmic scale.
- The graph shows a decline in gain as the frequency increases, which is characteristic of a low-pass filter, meaning it allows low frequencies to pass through while attenuating high frequencies.
- At the lower end of the frequency spectrum, the gain is highest, starting just above 12 dB, then decreases steadily with increasing frequency.
- The phase of the output voltage also changes with frequency, as indicated by the dotted line, which shows the phase angle in degrees. It starts near 0 degrees and drops toward -90 degrees as the frequency increases, which is typical for a capacitive circuit.

Summary:

The circuit functions as a low-pass filter, as evidenced by the high initial gain at low frequencies and the steady decline of gain with increasing frequency. The presence of multiple capacitors in parallel is likely to increase the overall capacitance, contributing to a more pronounced filtering effect at lower frequencies. The steepness of the gain roll-off suggests a strong filtering action, which would be more pronounced than a single-capacitor setup. This could be part of a power supply design where the goal is to smooth out the ripple from a rectified voltage or to filter out high-frequency noise from a signal. The phase shift toward -90 degrees at higher frequencies is consistent with the behavior of capacitors, which introduce a phase lag in AC circuits.

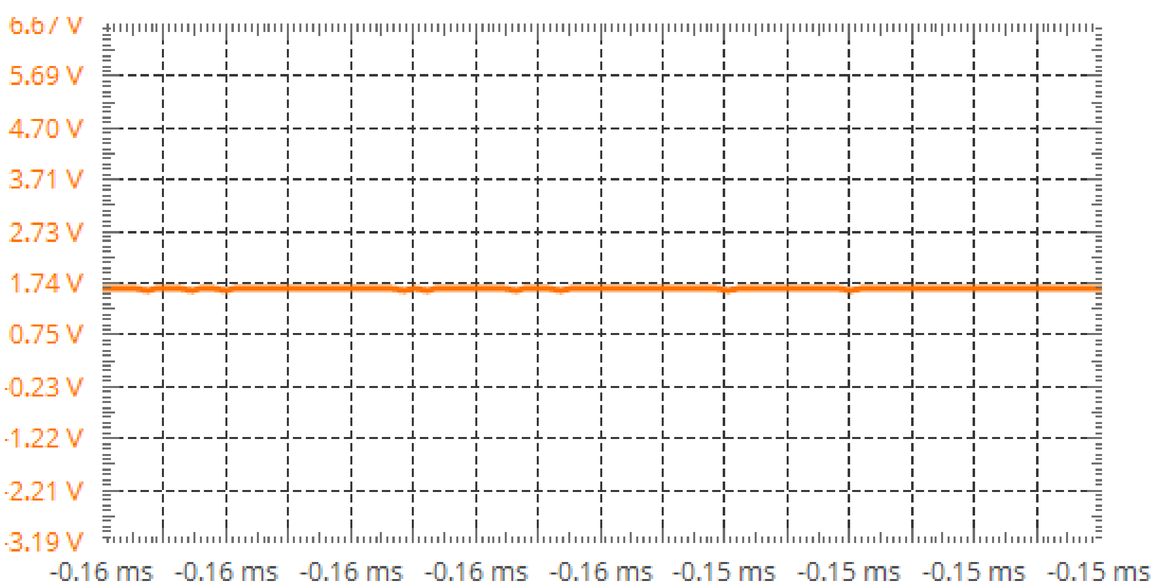
Experimental Data :

Input (from rectifier):



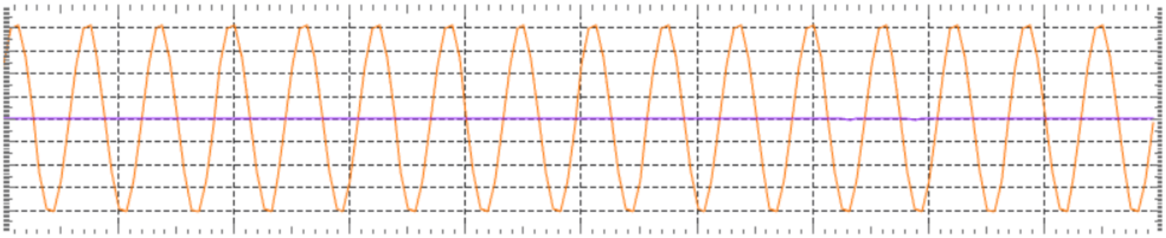
- The input waveform is an oscillating signal, which is a rectified AC waveform
- The voltage peaks at approximately 6.54 V and dips to around 3.39 V. This is indicative of a rectified signal that has not been fully smoothed out

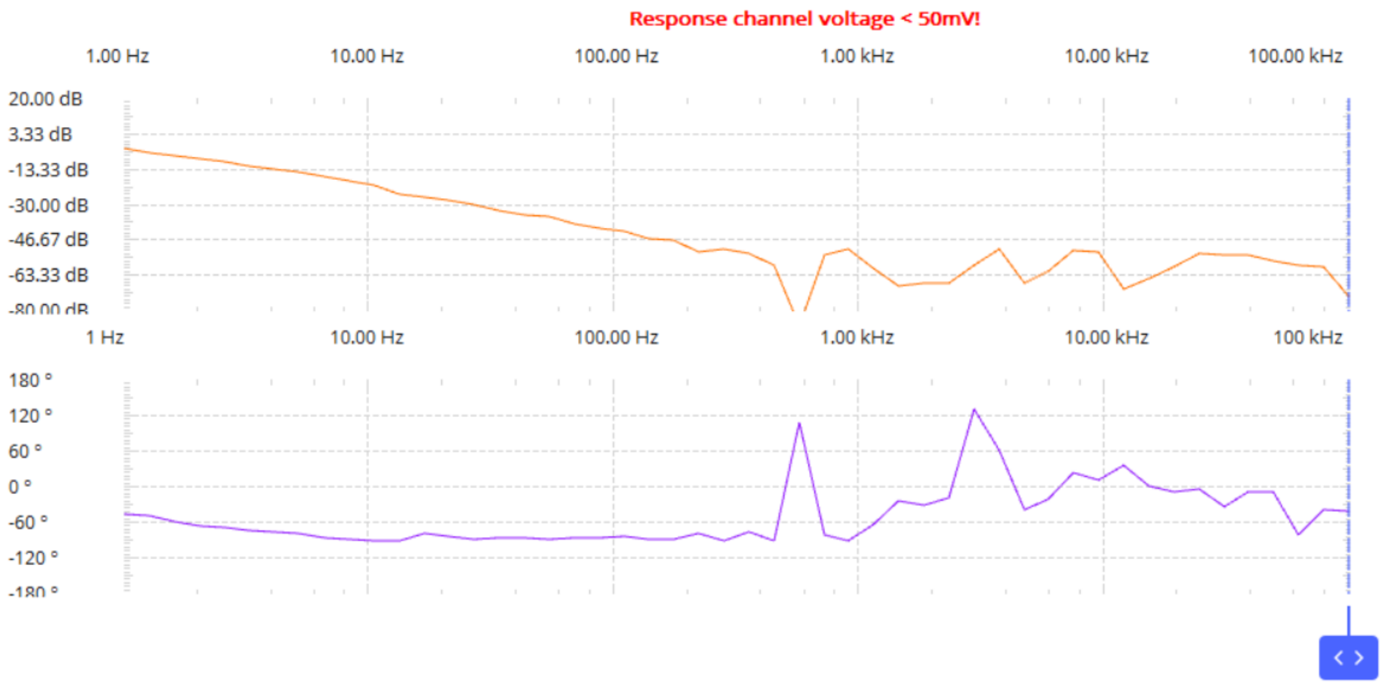
Output:



- The output waveform appears to be a DC signal with very little to no observable ripple.
- It shows a relatively flat line, indicating that the voltage is steady.
- The voltage level of the output is approximately 0.23 V, which is significantly lower than the peak of the input waveform.

Bode Plots:





Results:

Our filter analysis yielded comprehensive insights into the behavior of a capacitor-based low-pass filter when subject to an AC input signal. The circuit, comprising a series resistor and a parallel arrangement of four 330µF capacitors, was simulated and tested to assess its frequency response and effectiveness in producing a stable DC output from an AC input.

Simulation Findings:

- The simulated frequency response graph demonstrated the expected behavior of a low-pass filter, with a magnitude response decreasing as frequency increased. This response is in line with the calculated cutoff frequency of 120.57 Hz, where the response drops by -3dB, indicating the filter's effective bandwidth.
- The phase response graph revealed a -90 degree shift consistent with a capacitive reactance, indicating that the signal's phase lag increases with frequency.

Experimental Verification:

- Input signal measurements post-rectification presented an oscillating voltage with peaks around 6.54V and troughs near 3.39V. This behavior suggested an incomplete smoothing of the AC signal, as evidenced by the presence of ripple.

- The output voltage observed was a near-flat DC signal with negligible ripple and an average level of approximately 0.23V, indicating substantial attenuation of the AC component.

Despite the significant reduction in voltage from the rectified input to the filtered output, the filter's behavior aligns with the characteristics of a first-order low-pass filter. The low output voltage suggests that the filter, while effective in smoothing, also introduces a substantial voltage drop, which could be attributed to the combined impedance of the capacitors at the tested frequency range.

These results validate the filter's role in a power supply circuit to diminish noise and fluctuations, creating a more stable DC level suitable for electronics requiring clean power. However, the considerable voltage drop necessitates further steps for voltage regulation to ensure the output meets the necessary operational criteria for practical applications.

Concept 3: Phasor Analysis

Description:

With a phasor analysis we can observe the properties of a circuit with capacitors and resistors powered by an AC source. A phasor is a complex number that represents the sinusoidal function. We are going to analyze the IRMS and VRMS of the circuit as well as the impedance. In our circuit we have a capacitor and a resistive load. This resistive load will represent the powering of an LED and a resistor. However, because a diode has nonlinear behavior, the resistor will be its placeholder. The capacitor in the circuit as mentioned previously serves to smooth out the voltages coming from the rectifier. The diodes that make up the rectifier do have a small impedance. However, such properties of diodes are nonlinear and difficult to represent. For the sake of our phasor analysis, we will disregard the small impedances produced by these diodes in our circuit.

NOTE**: Originally, we decided to use a high frequency, however I realized that it created large discrepancy in the phasor analysis. For this proof of concept mathematical and simulation portion, I lowered the frequency to 60Hz produce much more realistic values. 60Hz is also the value used for the simulations.

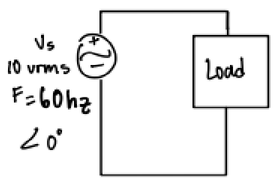
Analysis:

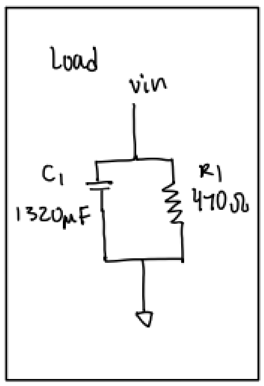
In this phasor analysis we have an RC circuit in parallel. This means that we need to find the impedances of both components and combine them to find the equivalent resistance. After we get the equivalent resistance in the imaginary domain, we convert to phasors. This involves polar form.

Phasor Analysis

After Transformer

$V_S \approx 10V_{RMS}$





$\omega = 2\pi(60) = 376.9911$

$I_{RMS_{Load}}$ — want to solve for

$$Z_{C1} = \frac{1}{j\omega C} = \frac{1}{j(376.9911)(1320)(10^{-6})} = -j2.0095$$

$$Z_R = 470$$

$$Z_{C1R1} = \frac{Z_{C1}+Z_{R1}}{Z_{R1}Z_{C1}} = \frac{Z_{R1}Z_{C1}}{Z_C+Z_{R1}} = \frac{1}{j\omega C+\frac{1}{R}}$$

$$\frac{1}{j(251327.412)(1320\times10^{-6})+\frac{1}{470}} = -j2.0095$$

$$V_{RMS}/Z_{C1R1} = I_{RMS}$$

$$\frac{10\angle 0^\circ}{2.0095\angle -90^\circ} = 4.9764A\ \angle -90^\circ = I_{RMS}$$

Simulation:

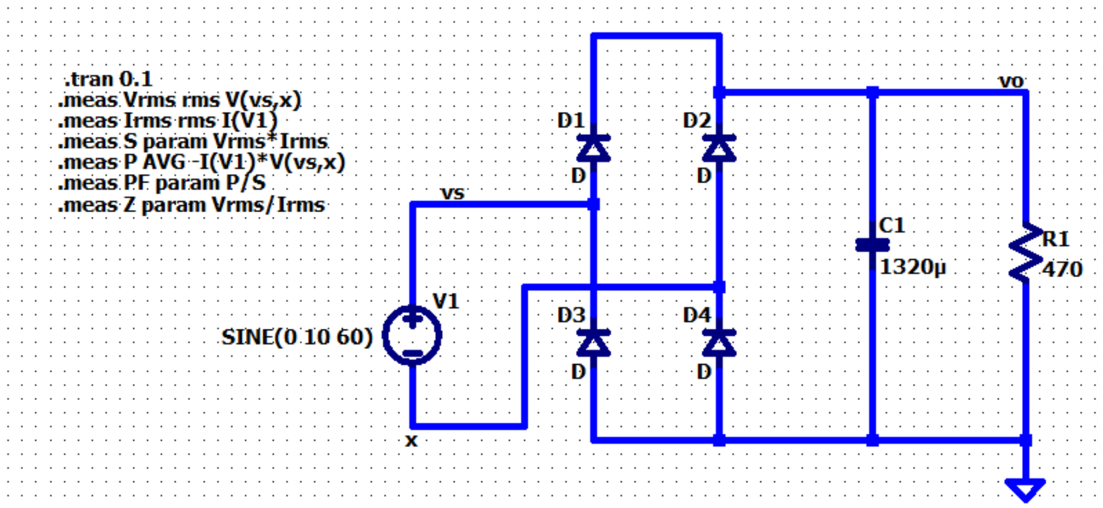
In our LT Spice simulation, we can see that the values of IRMS and VRMS from the entire circuit can be measured. We can also get the measured impedance by using Ohms law.

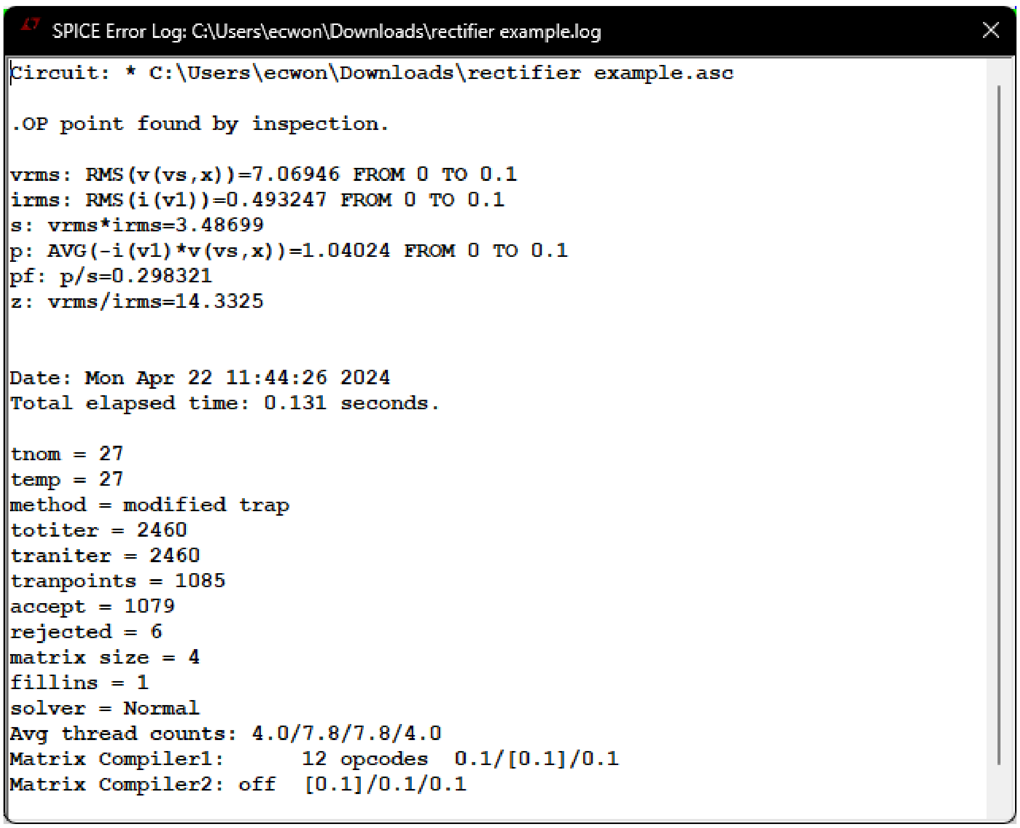
Our simulations produced:

VRMS: 7.06946

IRMS: 0.493247

Z (total impedance): 14.3325 ohms




SPICE Error Log: C:\Users\ecwon\Downloads\rectifier example.log

```
Circuit: * C:\Users\ecwon\Downloads\rectifier example.asc

.OP point found by inspection.

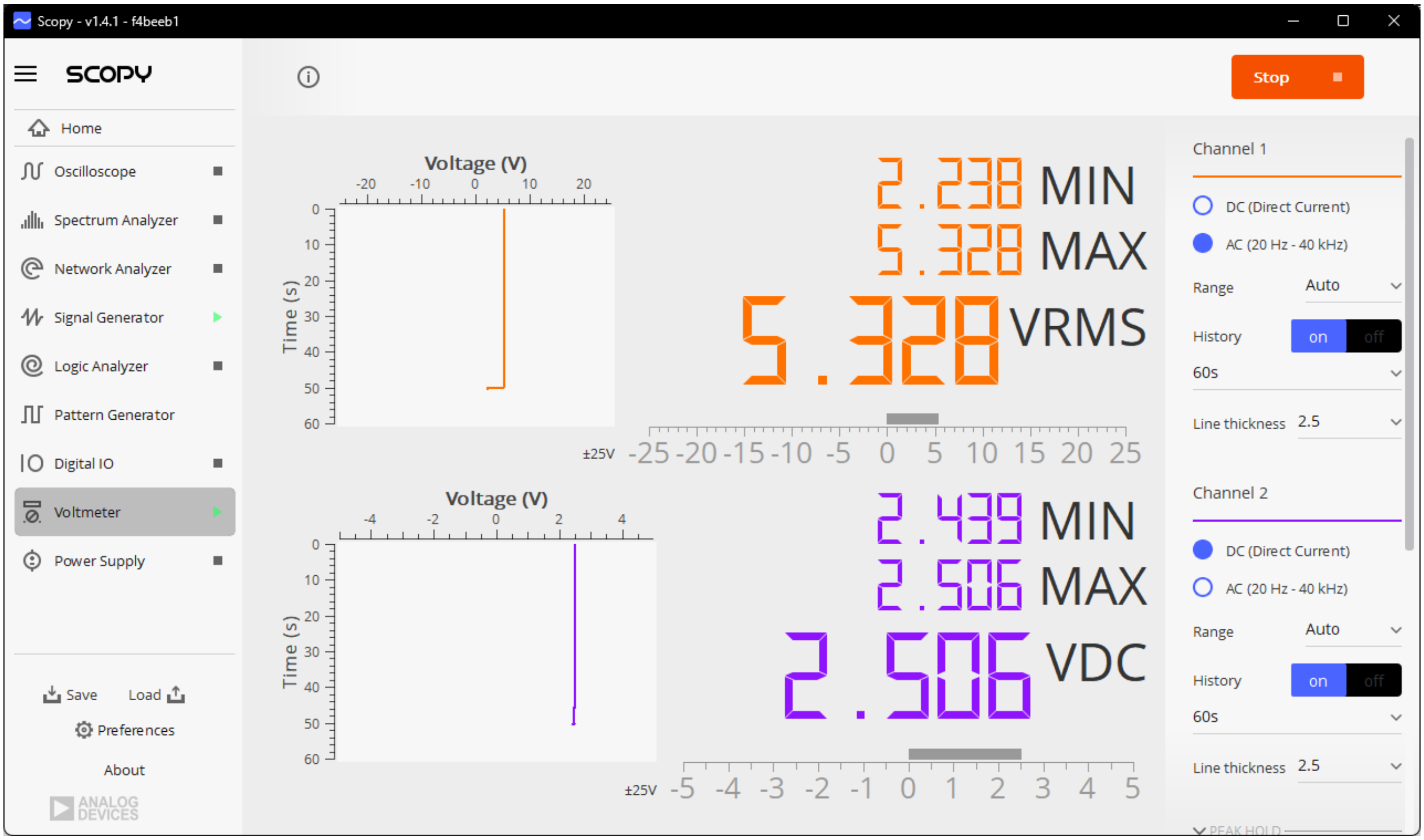
vrms: RMS(v(vs,x))=7.06946 FROM 0 TO 0.1
irms: RMS(i(v1))=0.493247 FROM 0 TO 0.1
s: vrms*irms=3.48699
p: AVG(-i(v1)*v(vs,x))=1.04024 FROM 0 TO 0.1
pf: p/s=0.298321
z: vrms/irms=14.3325


Date: Mon Apr 22 11:44:26 2024
Total elapsed time: 0.131 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2460
traniter = 2460
tranpoints = 1085
accept = 1079
rejected = 6
matrix size = 4
fillins = 1
solver = Normal
Avg thread counts: 4.0/7.8/7.8/4.0
Matrix Compiler1:      12 opcodes  0.1/[0.1]/0.1
Matrix Compiler2: off  [0.1]/0.1/0.1
```

Experimental Data:

In our experimental measurements we were only able to measure VRMS as scopy voltmeter can measure AC sources ranging from frequencies of 20Hz to 40KHz. However, scopy cannot measure the IRMS. In order for us to measure the IRMS we must divide by our estimated impedance. By dividing our input of 5.328 VRMS by an impedance of 2ohms we get approximately and IRMS of 2 Amps.



Results:

Our measurements are not accurate in line with the simulations or experimental data due to the impedances generated from our rectifier and our LED load. Additionally, for our simulation we had to run high frequencies for the inductor to be effective. I believe that the discrepancy for the IRMS compared to the simulation and mathematical analysis stems mainly from the impedances generated by all the other components in the circuit. Additionally we cannot measure IRMS with scopy so we cannot verify any of our results experimentally with regards to our IRMS.

Concept 4: Complex Power

Description:

In our project power is a very important aspect. As we are modeling a power grid, this gives us certain requirements to be able to efficiently and effectively transmit power. For our purposes, we are modeling an AC source coming from things such as wind turbines. In order for homes to be able to use that power generated from an AC source, we need to use a rectifier. Additionally connected to these systems are filters of sorts that help us achieve a more stable output from AC to DC. DC is what our home appliances and electronics use. When using filters, we can cause inefficiencies in our systems if they are not balanced. In class we learned that capacitors could lag current while inductors and cause current to be leading. In our system we only used a capacitor and through LT spice and mathematical calculations we can determine that without an inductor our current and our voltage are not in phase.

NOTE**: Originally, we decided to use a high frequency, however I realized that it created large discrepancy in the phasor analysis. For this proof of concept, I lowered the frequency to 60Hz to produce much more realistic values. 60Hz is also the value used for the simulations.

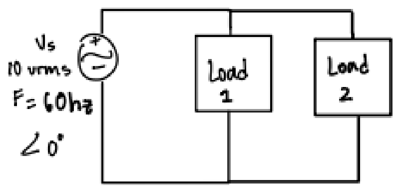
Analysis:

Here we see that while we do not have the most accurate representation for our impedance, we can clearly determine that with only a capacitor, we do not have optimal efficiency. In order to achieve higher efficiency, we would need to add an inductor this would reduce the loss of reactive power and overall give us more efficiency. For the inductor I also included a small resistive value to better represent a real-world capacitor.

Complex Power

$V_s \approx 10 V_{RMS}$

Load 2
A capacitor 1320μ ; small 1Ω loss



Load 1
A resistor representing an LED and resistor as a load

$w = 2\pi(60) = 376.9911$

$$Z_{Load\ 1} = \frac{1}{j(376.9911)(1320)(10^{-6})} = -j2.0095 + 1\Omega$$

$Z_{Load\ 1}$ phasor $= 2.2445 \angle -63.5433°$

$Z_{Load\ 2} = 470\Omega$

$Z_{Load\ 2}$ Phasor $= 470 \angle 0°$

Load 1

$P = \frac{(10)^2}{470}\cos(0) = 0.213$ W $\quad S = \sqrt{P^2 + Q^2} = 0.213$ VA $\quad pf = 1$

$Q = \frac{(10)^2}{470}\sin(0) = 0$ VAR

Load 2

$P = \frac{(10)^2}{2.2445}\cos(-63.5433) = 19.849$ W $\quad S = \sqrt{P^2 + Q^2} = 44.5533$ VA

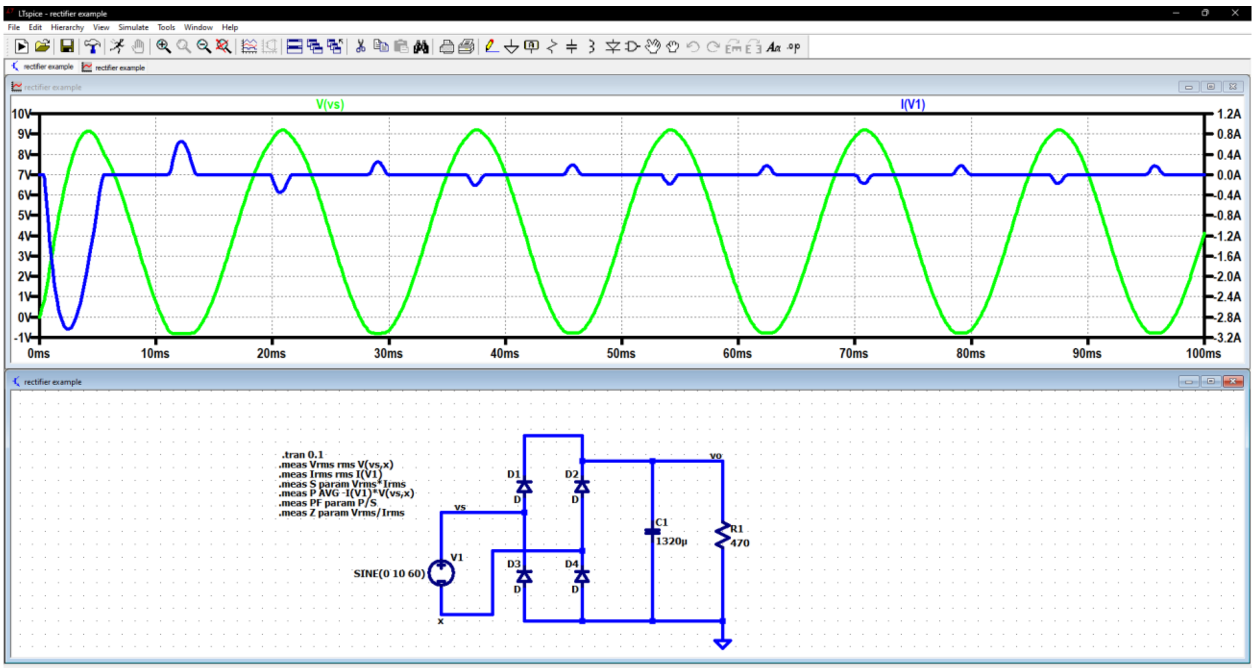
$Q = \frac{(10)^2}{2.0095}\sin(-63.5433) = -39.8873$ VAR $\quad pf = 0.4455$

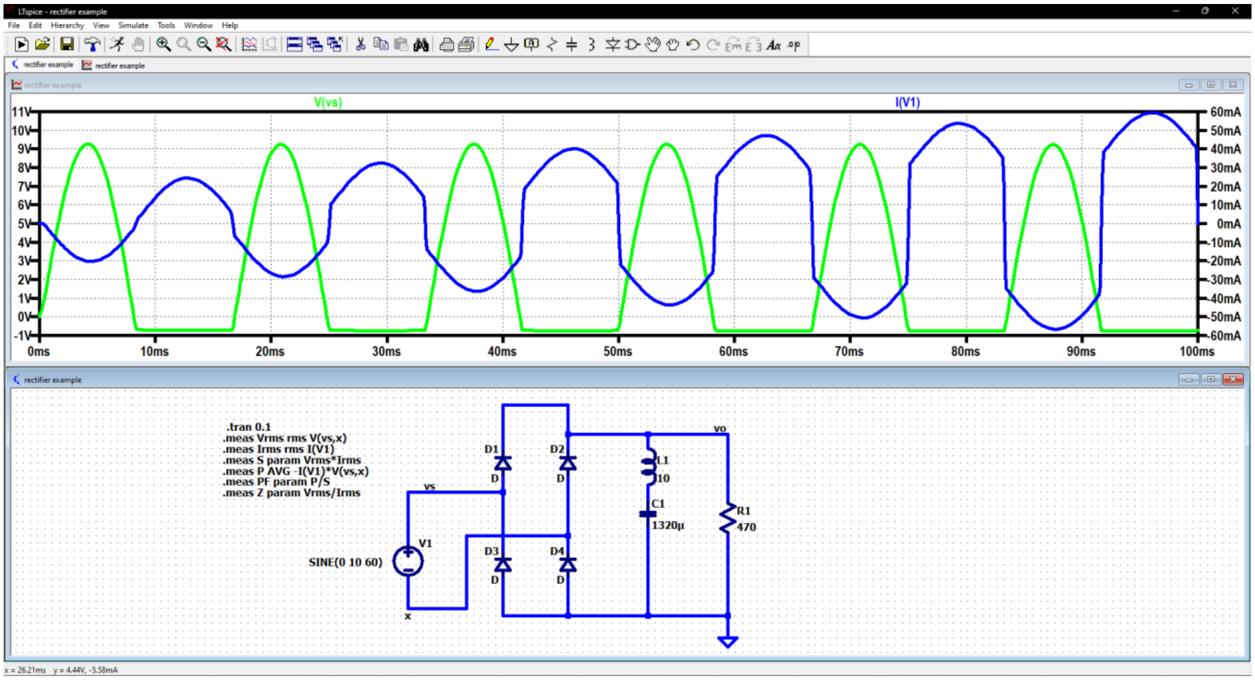
	P[W]	Q[VAR]	|S|[VA]	pf
Load 1	0.213	0	0.213	1
Load 2	19.949	-39.8873	44.5533	0.4455
Source	20.062	-39.8873	44.7663	0.44814

Some things to improve the efficency is to add a inductor in series with the capacitor.

Simulation:

In our simulation we can clearly see that without an inductor we have spikes in our current that is out of phase. This causes large inefficiencies. When we add in an inductor, we can see that the spikes even out and better match the phase of the voltage function. This proves our predictions that adding an inductor in series would be beneficial in increasing the efficiency of our power grid.





SPICE Error Log: C:\Users\ecwon\Downloads\rectifier example.log

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Circuit: * C:\Users\ecwon\Downloads\rectifier example.asc

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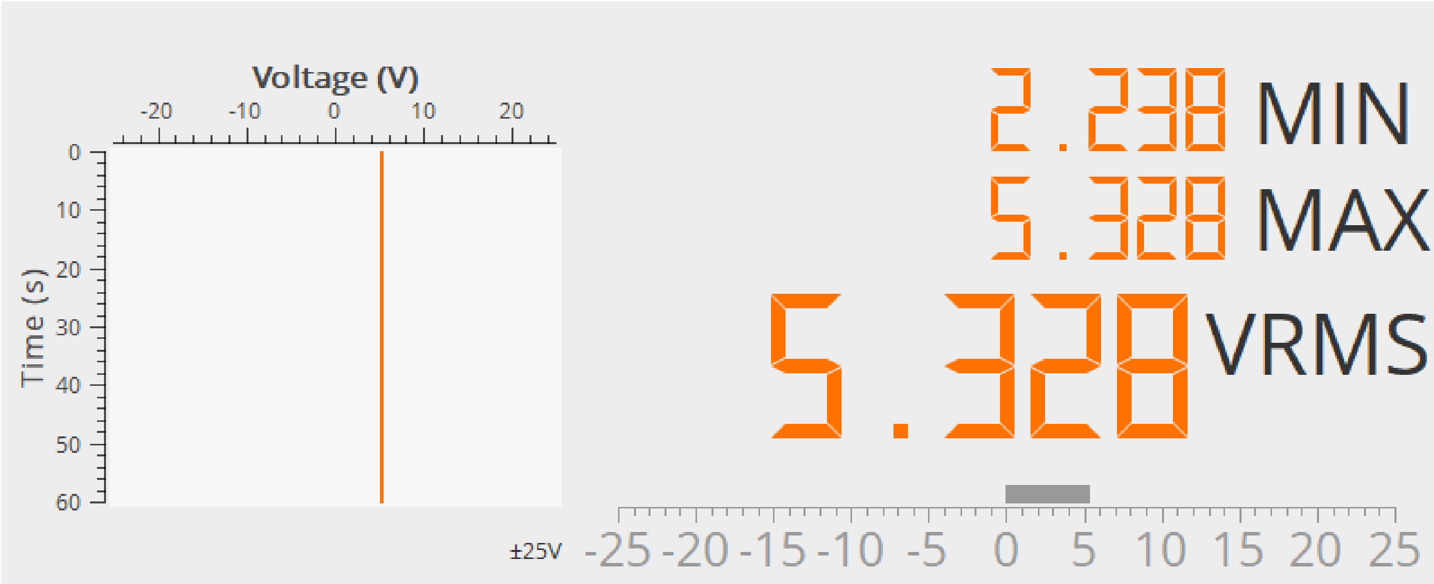
irms: RMS(i(v1))=0.493247 FROM 0 TO 0.1
s: vrms*irms=3.48699
p: AVG(-i(v1)*v(vs,x))=1.04024 FROM 0 TO 0.1
pf: p/s=0.298321
z: vrms/irms=14.3325


Date: Mon Apr 22 11:44:26 2024
Total elapsed time: 0.131 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2460
traniter = 2460
tranpoints = 1085
accept = 1079
rejected = 6
matrix size = 4
fillins = 1
solver = Normal
Avg thread counts: 4.0/7.8/7.8/4.0
Matrix Compiler1:      12 opcodes  0.1/[0.1]/0.1
Matrix Compiler2: off  [0.1]/0.1/0.1
```

Experimental Data:

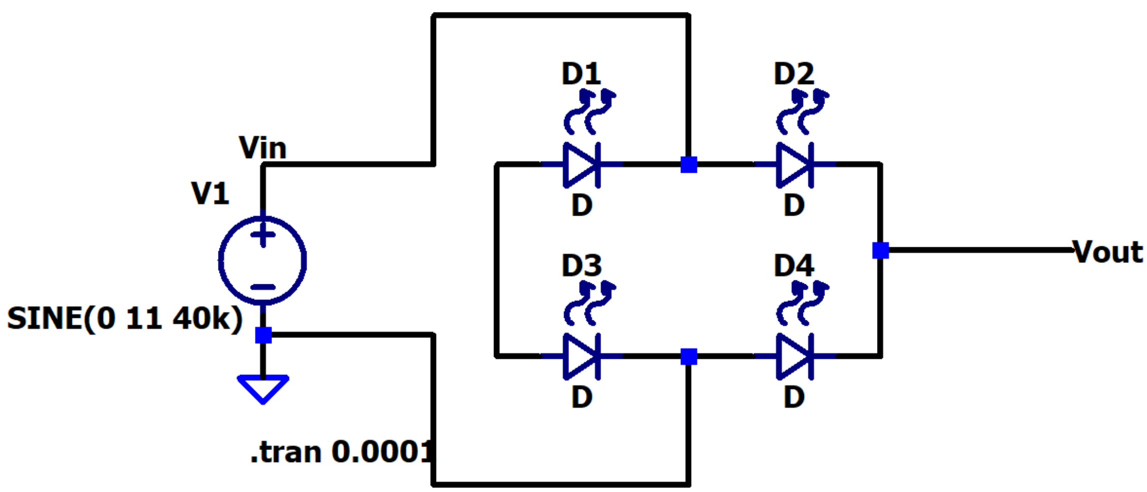
For our experiments we conducted we measured were only able to measure the VRMS and not the IRMS. However, we can estimate the amount of power across the resistor as there is no phase change for linear components such as a resistor. By dividing our voltage by our impedance of about 470 ohms we get IRMS. IRMS times VRMS gives us power. Taking 5.328/470 gives us 0.0113 A. To get power be multiple 5.328V by 0.0113A. This gives us 0.060 watts. This is lower than what we get from our simulation. However, we can clearly see that power is being transmitted across the resistive load. Also it is important to note that in our experiments we had to run high frequencies in order to get our inductor to function.



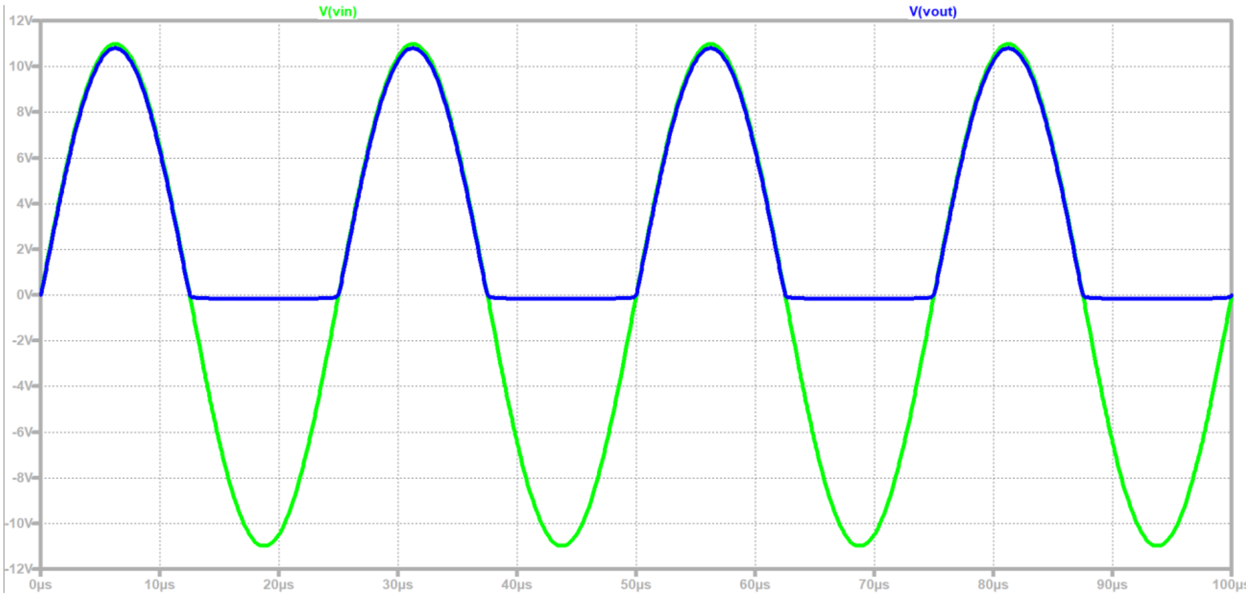
Results:

Overall, our mathematical analysis, simulations, and experimental data may have differences due to not being able to find small impedances from the diodes and wires in the system. This can affect how much real power is being generated. This can explain the large loss of real power across the resistor.

Rectifier:



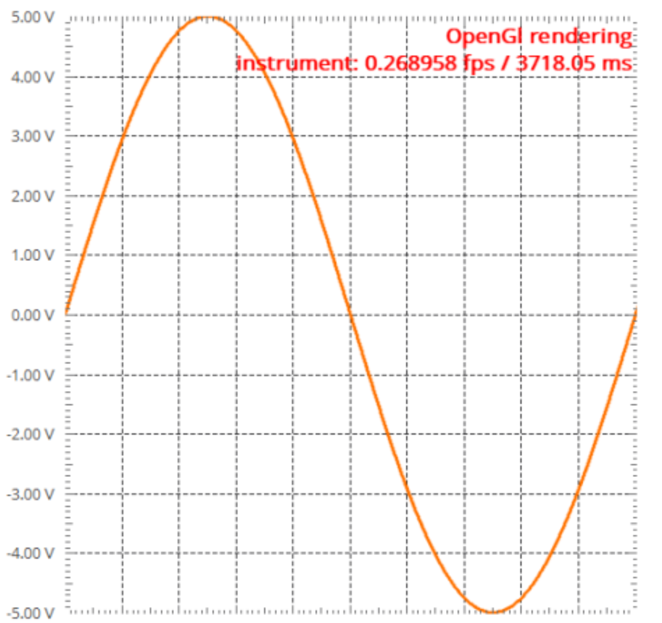
Simulation:

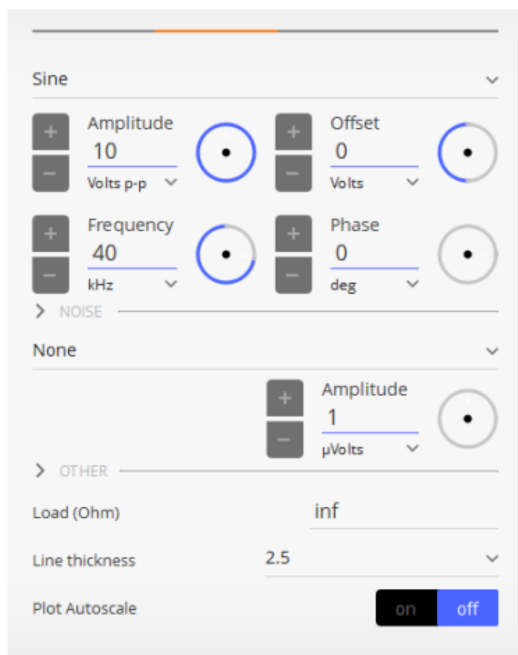


The green is the input and the blue is the output

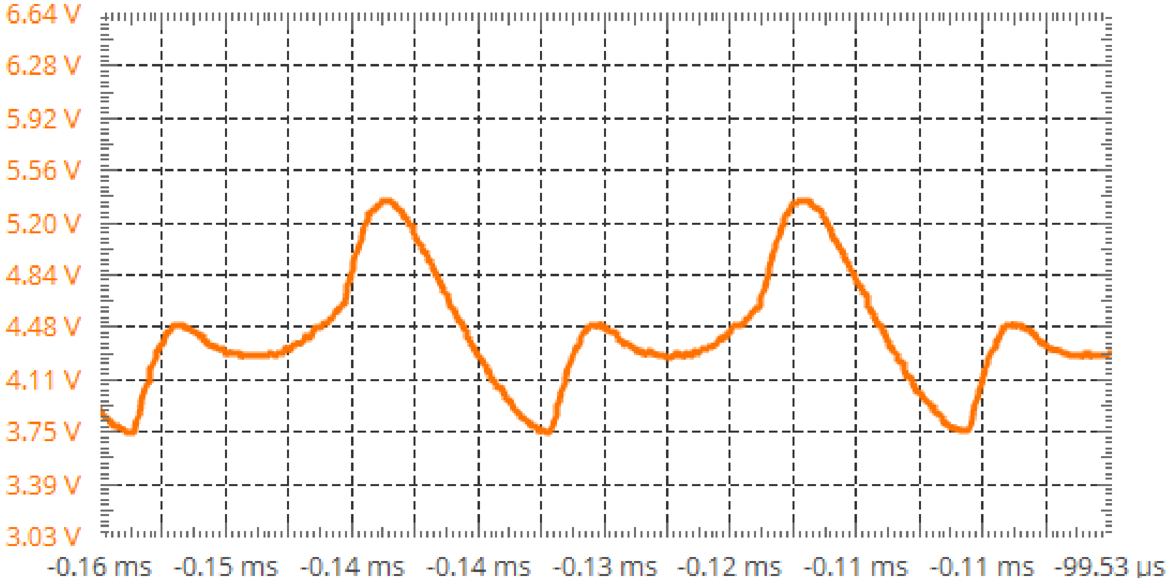
Measurements:

Input:





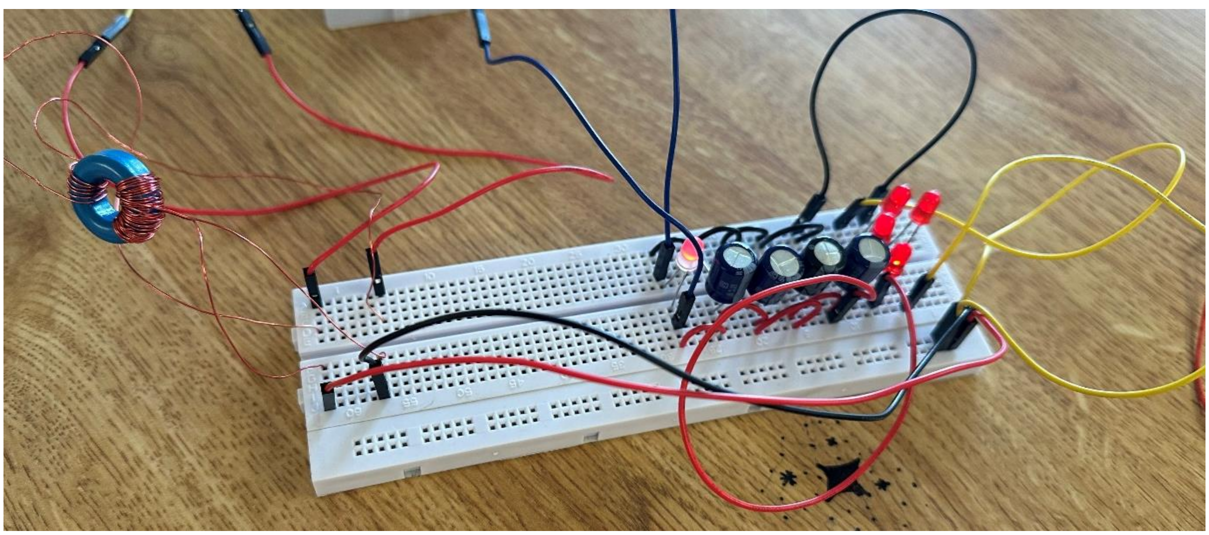
Output:

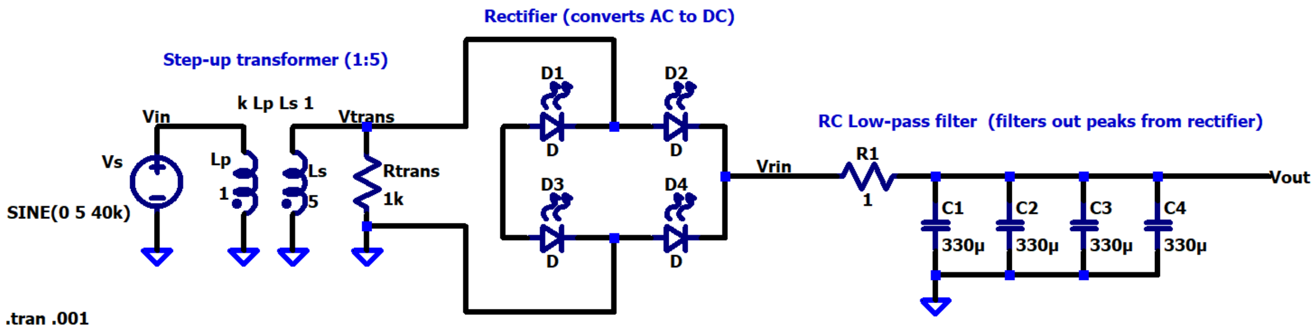


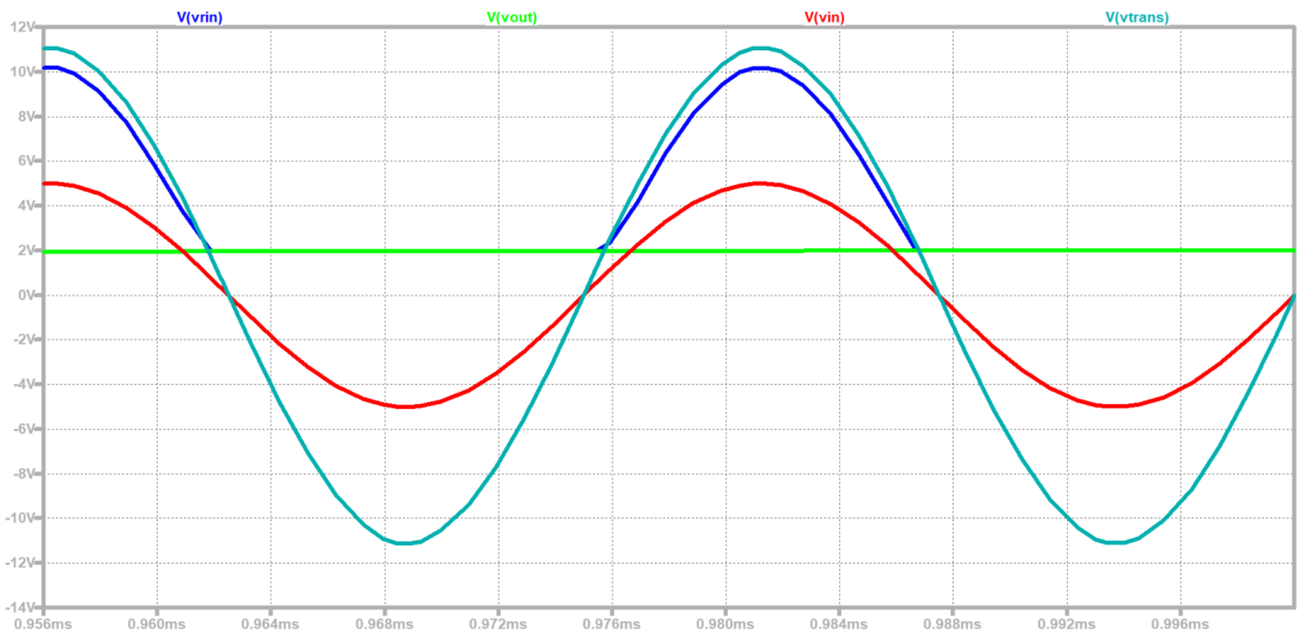
Results:

The purpose of the rectifier is to convert our AC voltage from the wind turbine (simulated by the M2K waveform) to DC voltage that we can easily combine it with our solar panel's voltage. As you can see here from the simulation it uses 4 diodes (in our case we used LEDs because that is all we had however they are incredible inefficient). You put the diodes in a way so you “convert” the current to only going one direction since diodes only let current to flow in one direction. So, in our case we cut the bottom of the waveform off and are only left with the positive voltage. In practice this worked however the wave for became distorted most likely do to the fact we were not using ideal components.

Whole Circuit:

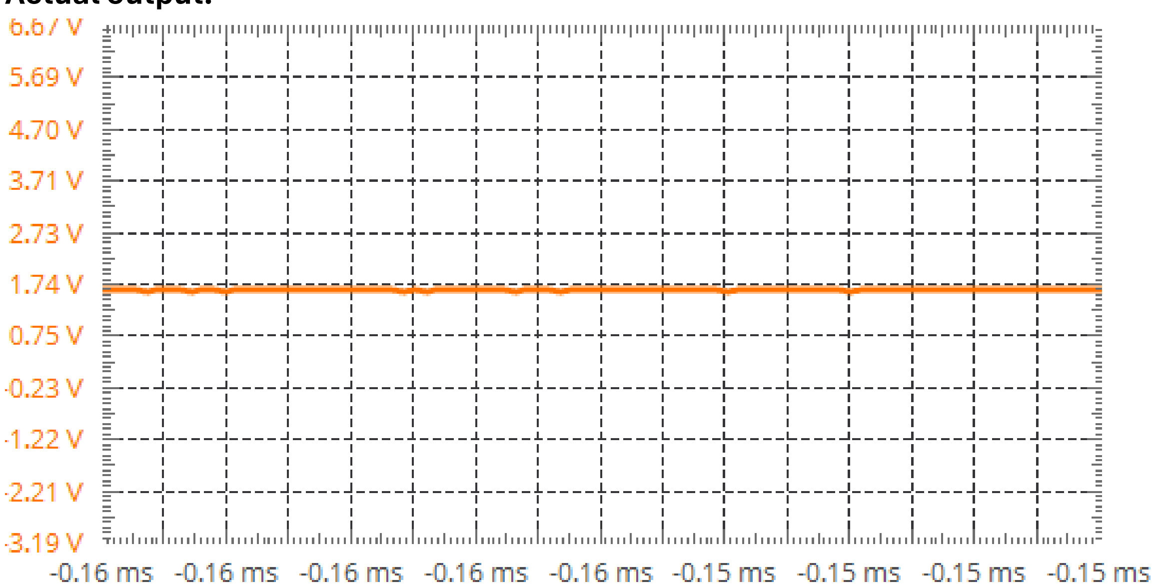






- The red is the input voltage
- The light blue is the output voltage from the transformer
- The dark blue is the output from the rectifier
- The green is the output voltage

Actual output:



Results:

As shown in the simulation of the whole circuit we first pass the input voltage through a step-up transformer to step up our AC voltage. We then put that voltage through a rectifier to convert it to DC voltage, and finally we put that through a filter to smooth is out and make it a constant voltage source. In the simulation we get a output of 2V and in the actual circuit we get an output of about 1.74V which is very close. The loss of 0.26V could be from a few different factors; the biggest factor is we are not dealing with ideal components in real life, components have internal resistance as well as the wires have internal resistance. So, all in all the outputs align well.

Future improvements:

While the circuit designed has demonstrated adequate performance, there are several areas identified for future improvement:

1. **Component Optimization**: The selection of more efficient components, such as Schottky diodes for the rectifier, could minimize voltage drops and improve overall circuit efficiency.
2. **Thermal Management:** As the system scales, heat dissipation becomes critical. Incorporating heat sinks or thermal management techniques would prolong component life and ensure stable operation.
3. **Voltage Regulation:** To address the substantial voltage drop observed, incorporating a voltage regulator could stabilize the output, providing a consistent voltage level suitable for charging batteries or powering electronic devices.
4. **Energy Storage Integration**: Exploring the integration with energy storage solutions would be vital for continuous power supply during periods when wind or solar power is insufficient.
5. **Enhanced Filtering Techniques**: Given the importance of filtering in AC to DC conversion, researching advanced filtering techniques or materials could yield a cleaner DC output, thus reducing electronic noise in sensitive applications.

Putting all the labs together:

Now that we have completed all three omega labs, we can discuss how they all go together. First, we will utilize what we used in this lab to get AC voltage from wind power and convert that to DC. We will then combine that with our solar panels we used in labs 1 and 2. We then will utilize our timer in lab 2 to check if it is day or night so we can charge our batteries during the day when the sun is out. During the night we will switch the renewable energy into our comparator and check if the renewable energy is greater than the non-renewable energy. We will then output whatever voltage is greater into the power grid.

What we learned:

In this particular lab session, we developed a range of practical skills. A key learning outcome was mastering the conversion of AC to DC voltage, along with navigating the inherent challenges this process presents. These challenges were primarily due to the imperfections in components and occasional shortages of necessary materials. Additionally, we gained hands-on experience in constructing transformers tailored to specific needs—whether for stepping up, stepping down, or maintaining voltage levels. We also enhanced our understanding of filters, focusing especially on filter analysis using Bode plots and their simulation. This comprehensive skill set significantly deepened our practical understanding in these areas.

Questions we have:

The current project has led to several questions that would guide future research and development:

1. How can we optimize the transformer design to reduce magnetic and copper losses further?
2. What is the impact of different rectifier configurations on the efficiency and quality of DC output?
3. How do variations in wind turbine output affect the performance of the circuit, and what compensatory mechanisms can be employed?
4. What are the best practices for integrating multiple renewable energy sources into a unified power management system?
5. What materials or technologies could be leveraged to improve capacitor performance in the filtering stage?
6. Are there alternative energy storage solutions that could be more effective or efficient in this system?