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ESE 215 - 103 (Circuits Laboratory)
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Midterm Lab: Making an AC/DC Power Supply

Introduction

Background/Breakdown of Specification

In our Midterm Project for ESE 215, our ultimate objective was to make a power supply by converting an AC voltage supply (one that varies with time from +x to –x) to a DC one (stays at x regardless of time), given a transformer, diodes, zener diodes (which permit a predetermined maximum voltage across), resistors, and capacitors. Throughout the laboratory, we used an oscilloscope to measure progress and make sure individual parts of the circuit (described in depth in the prelab) were functioning properly. Our goal was to create a DC voltage of approximately 12 V with a ripple voltage that is a maximum of 2% of this. To achieve this end, we had to conquer many tasks that led up to the creation of a DC power supply. First, we had to understand and implement a transformer, which essentially took the $115V_{rms}$ supplied by the wall outlet and toned it down to $18V_{rms}$ by inducing current via a system of two inductors with different numbers of coils. Then, using four diodes (which allow current flow in only one direction), we added a full-wave rectifier to the circuit which contained a positive and negative rectifier to control the flow of current such that the voltage waveform would no longer traverse the x-axis. The positive rectifier would make the voltage waveform into 'repeated hills' that mimicked |sin(x)| rather than sin(x) itself. The negative rectifier had the same effect but below the x-axis. The next task consisted of building a smoothing filter using a load resistor (which would dissipate voltage across it to yield in a final output voltage closer to 12V) and capacitor (which stores and releases charge) which together operate conjointly to minimize the alternating nature of the waveform even further. We had to determine a resistance and capacitance that would optimize this process. Finally, the voltage regulator was attached to the filter: this consisted of a zener diode and a series resistor (R_S). We chose a zener diode that would not allow more than 12 V across it, and the series resistor served to separate the positive terminal of the capacitor from the zener diode. Note: the smoothing filter and voltage regulator were built for both the positive and negative rectifiers, as illustrated in the entire power supply schematic in the prelab.

Prelab: Hand Calculations

1. Transformer

The turn ratio can be calculated by observing the number of turns on each side of the transformer—namely: $Turn\ Ratio = \frac{N_{Primary}}{N_{Secondary}} = 6.389$. By definition, the voltage ratio equals the turn ratio (i.e. $Voltage\ Ratio = \frac{V_{Primary}}{V_{Secondary}} = \frac{N_{Primary}}{N_{Secondary}} = 6.389$). Power can be calculated by understanding that $Power = Voltage * Current$; furthermore, since $\frac{I_{Secondary}}{I_{Primary}} = \frac{N_{Primary}}{N_{Secondary}} = \frac{V_{Primary}}{V_{Secondary}}$, by cross multiplying, it is apparent that $V_{Primary} * I_{Primary} = V_{Secondary} * I_{Secondary}$, and thus the ratio of the powers on either side of the transformer is 1:1. The output RMS Voltage (V_{RMS}) can be calculated by observing that $\frac{V_{input}}{V_{output}} = \frac{N_{Primary}}{N_{Secondary}}$ where V_{input} is $115V_{RMS}$ and V_{output} comes out to be $18V_{RMS}$. This voltage then ultimately divides in half when it traverses both the top and bottom (positive and negative) portions of the rectifier.

2. Rectifier sub-component

We chose to use a full-wave rectifier such that the output voltage would not only always be non-negative, but moreover the signal would mirror the waveform of |sin(x)|, as a half-wave rectifier would result in an alternating pattern of a bell-curve and a flat zero (both of same width/period). The input voltage of $18V_{RMS}$ was hence split across both halves of the full rectifier—the top portion received $+9V_{RMS}$ or 12.73V ($9 * \sqrt{2}$) and the bottom portion received $-9V_{RMS}$ or -12.73V ($-9 * \sqrt{2}$). Across each half of the rectifier, there is a characteristic voltage drop (V_f) across the diodes of 0.6V given in Ulaby's textbook *Circuits: Third Edition* for the diodes we are using in this laboratory; thus the net voltage drop across both rectifiers is 1.2 V.

3. Smoothing Filter sub-component

In this laboratory, one objective was to maintain the ripple voltage within 2% of the 12.73V input described in the previous segment—namely: the ripple voltage ought to be less than or equal to 254.6 mV. In order to calculate the capacitor and resistor values related to the smoothing filter, I first had to determine the period of the rectified waveform (T_{rect}) which was nothing but the reciprocal of the frequency. Since the original waveform had a frequency of 60 Hz and the full-wave rectifier essentially shifts the negative half of the graph to imitate the top portion, the frequency exactly doubles to 120 Hz. Therefore, $T_{rect} = \frac{1}{120\ Hz} = 8.33\ ms$. Now I had to find the time it took for the filter's capacitor to charge (τ_{up}) and discharge (τ_{down}). $\tau_{up} = \frac{T_{rect}}{12} = 0.69\ ms$ and $\tau_{down} = 12 * T_{rect} = 100ms$. The capacitance is given by $C = \frac{\tau_{up}}{2*R_D}$ where $R_D = 0.042\ \Omega$ and hence the capacitance is 8.267 mF. Subsequently, since $R_L = \frac{\tau_{down}}{C}$, the load resistance is at least 12.096 Ω, although this is actually arbitrary as the load resistance (R_L) is determined by repeated efforts to ensure that the ripple voltage remains below 254.6 mV.

4. Discussion on voltage regulator sub-component

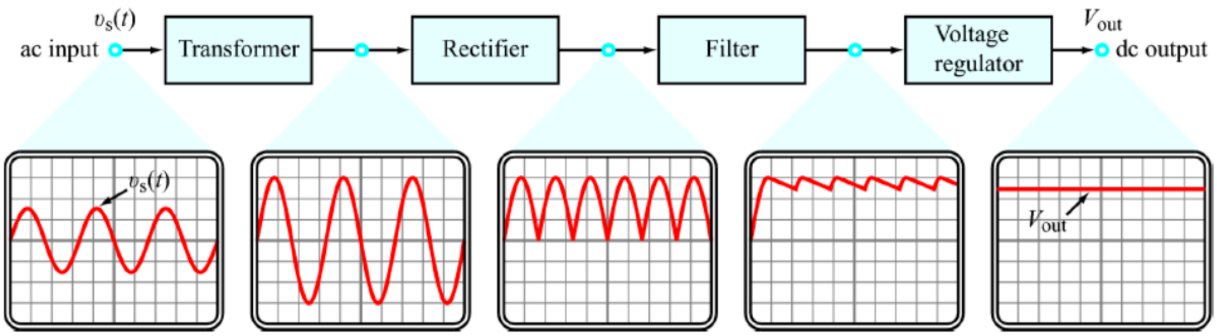
The purpose of the zener diode is to ensure a constant voltage of 12 V across it; thus in a sense, it regulates the voltage. The zener diode we implemented in our circuit was of the model D9 1N4733A and its properties included a V_Z of 12 V and came with an R_Z of 1 Ω. To calculate the ripple voltage (V_R) from the load resistance and the series resistance, I used the following equation: $V_R = [(V_{S1} - 2V_D) - V_2] * \frac{T_{rect}}{R_S C}[(R_Z||R_L)/[R_S + (R_Z||R_L)]]$. Plugging in 12.78V for V_{S1}, 0.6V for V_D, 8.267 mF for C, 12V for R_Z, 12.096 Ω for R_L, and setting the series resistance arbitrarily to 100 Ω, I was able to determine that the expected ripple voltage was 0.619 V.

5. Hand Calculation of power "budget" for entire system

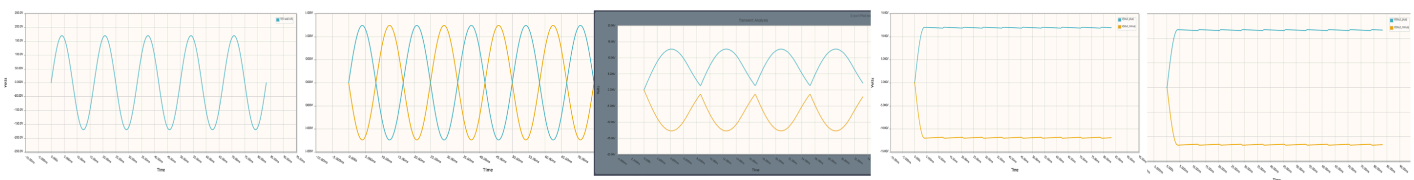
The thévenin equivalent resistance $R_{th} = \frac{V_{OC}}{I_{SC}}$ or the open-circuit voltage over the load resistor divided by the short-circuit current through the load resistor. By using an obscenely large resistance for the load to calculate via simulation the open-circuit voltage and using a very small resistance for the load to calculate via simulation the short-circuit current, I determined that $V_{OC} = 11.9\ V$ and $I_{SC} = 0.1085\ A$. Dividing these two, I obtain a thévenin equivalent resistance of 109.7 Ω. (Note: The thévenin voltage and currents are the open-circuit voltage and short-circuit current, respectively.) The maximum current that can be supplied to the load is equal to the short-circuit current found earlier: 108.5 mA.

6. Block Diagram of complete system

From *Circuits: Third Edition* (Ulaby):



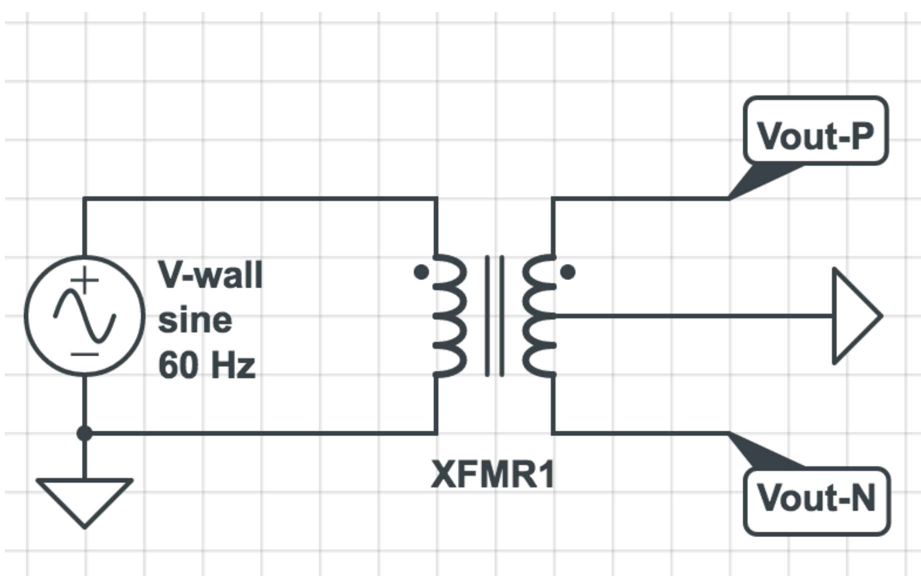
Custom Build Block Diagram from my own simulations with same steps (and including negative output):



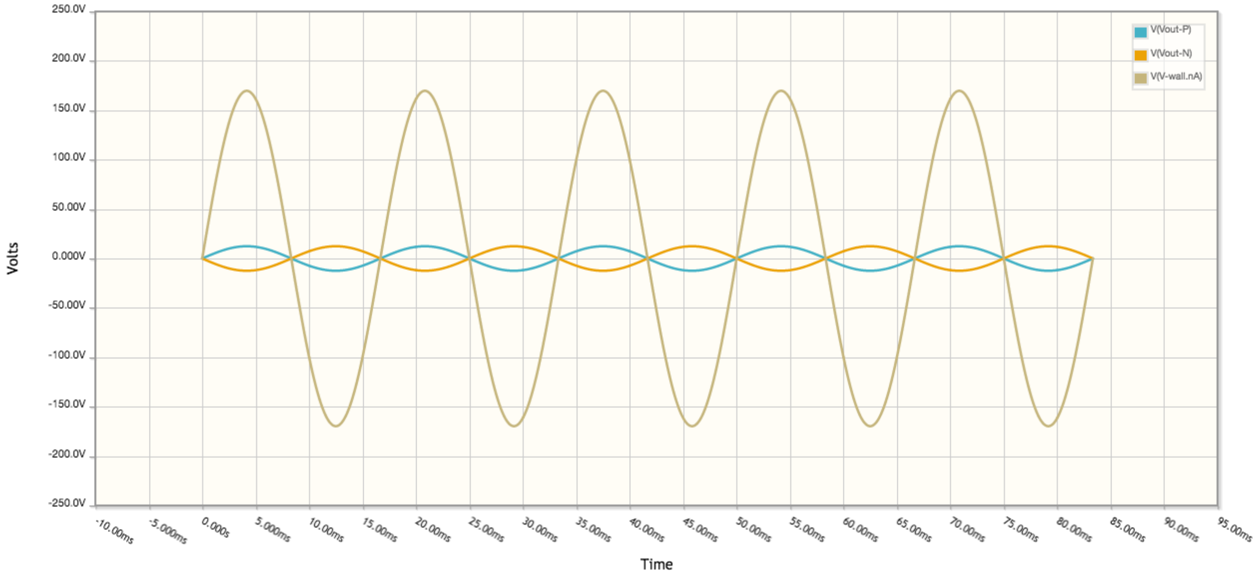
Prelab: Simulations

Transformer:

Schematic:

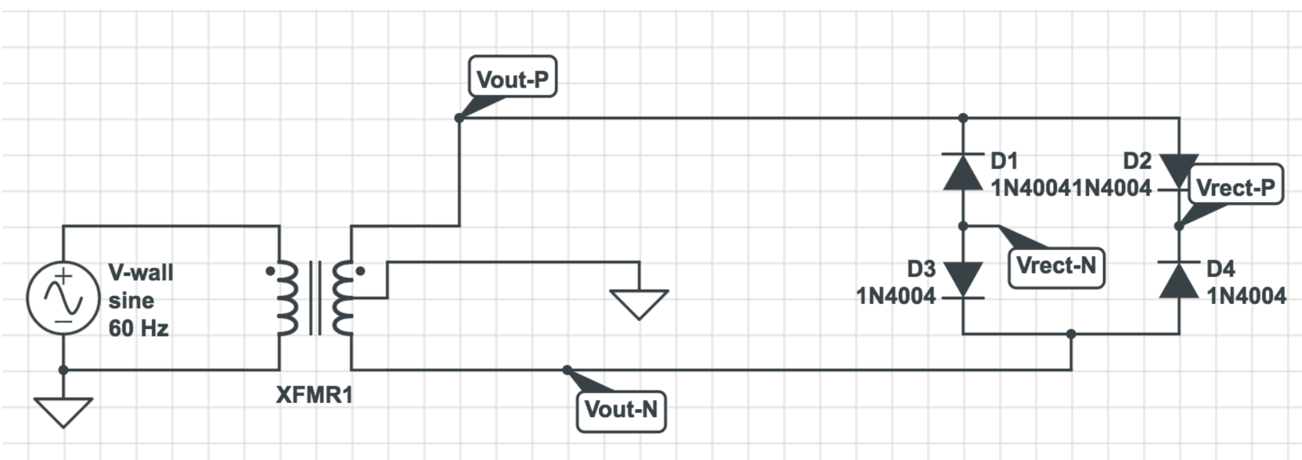


Time-domain simulation:

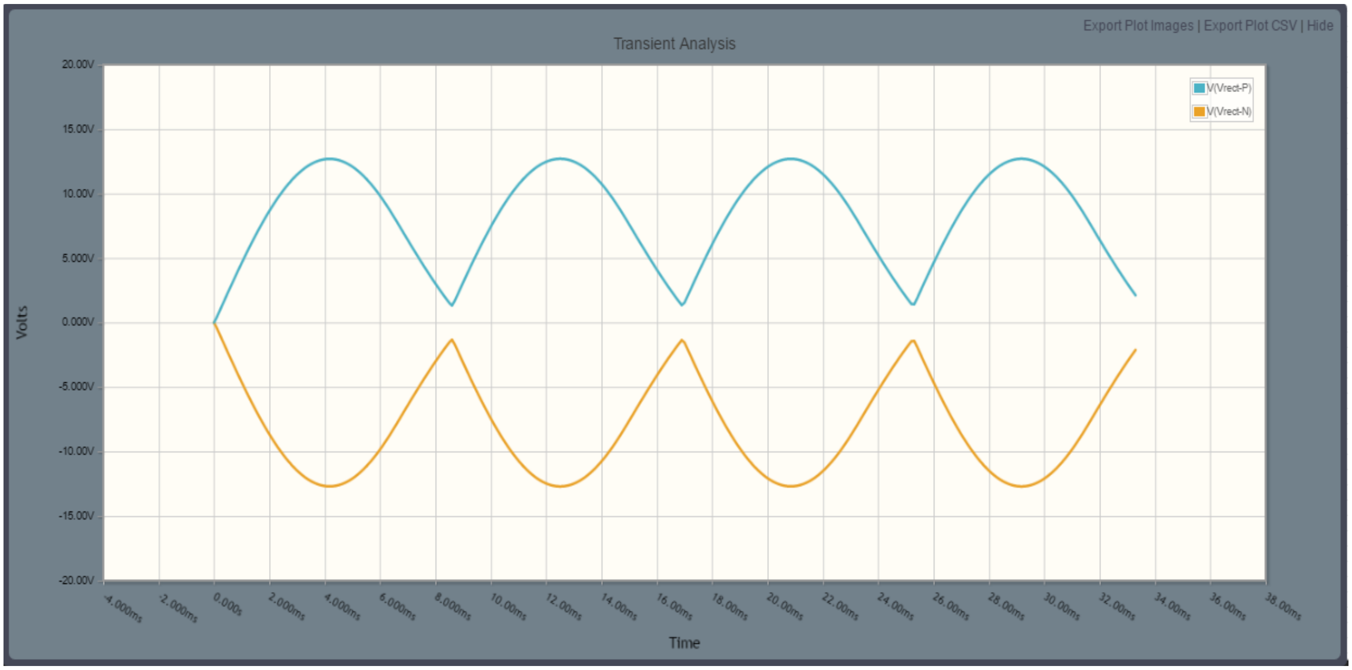


Full-Wave Rectifier:

Schematic:

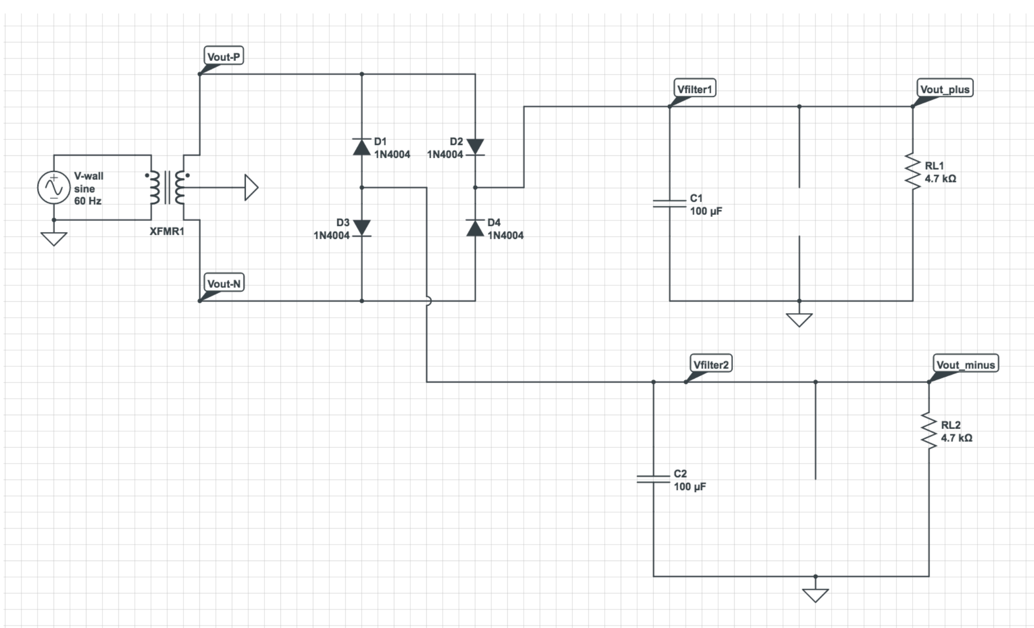


Time-domain simulation:

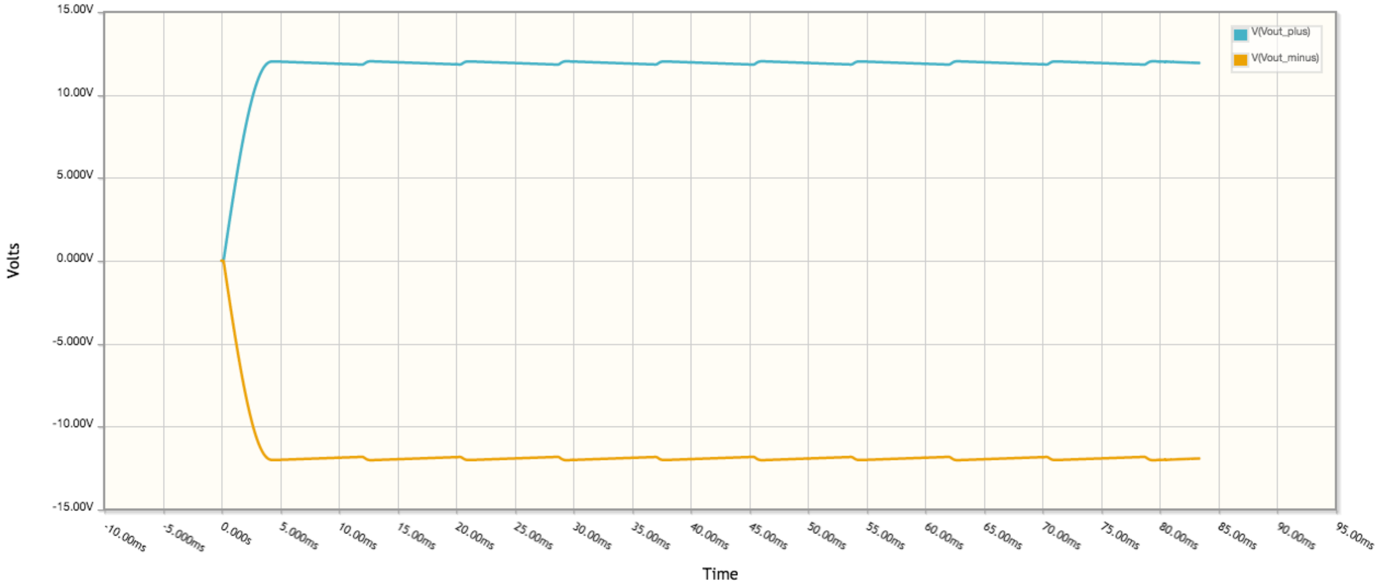


Smoothing Filter:

Schematic:



Time-Domain Simulation:

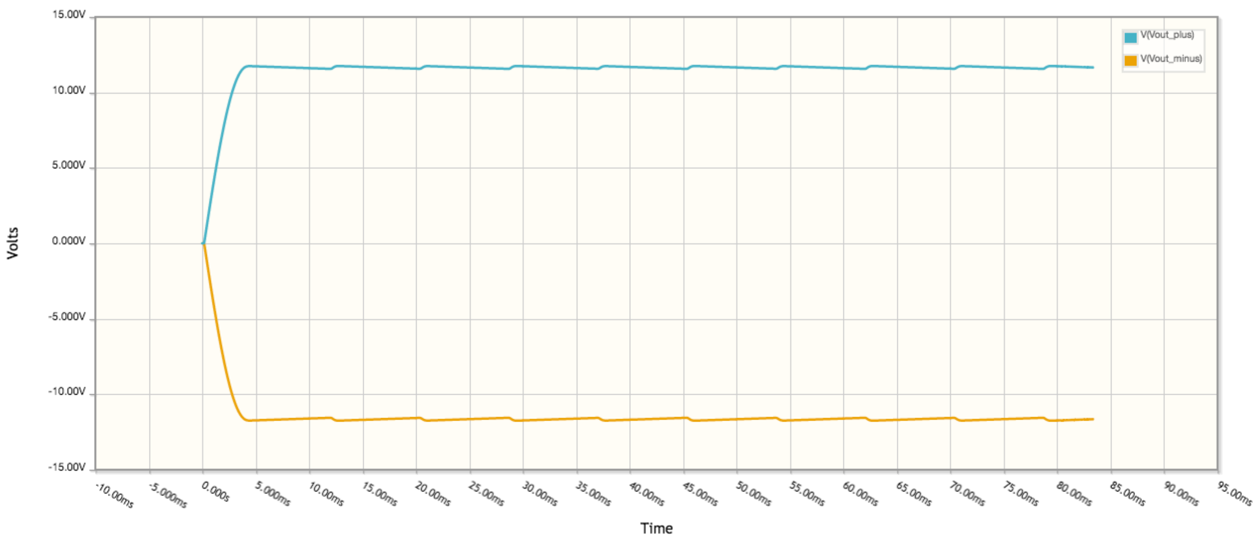


Voltage Regulator:

Schematic:

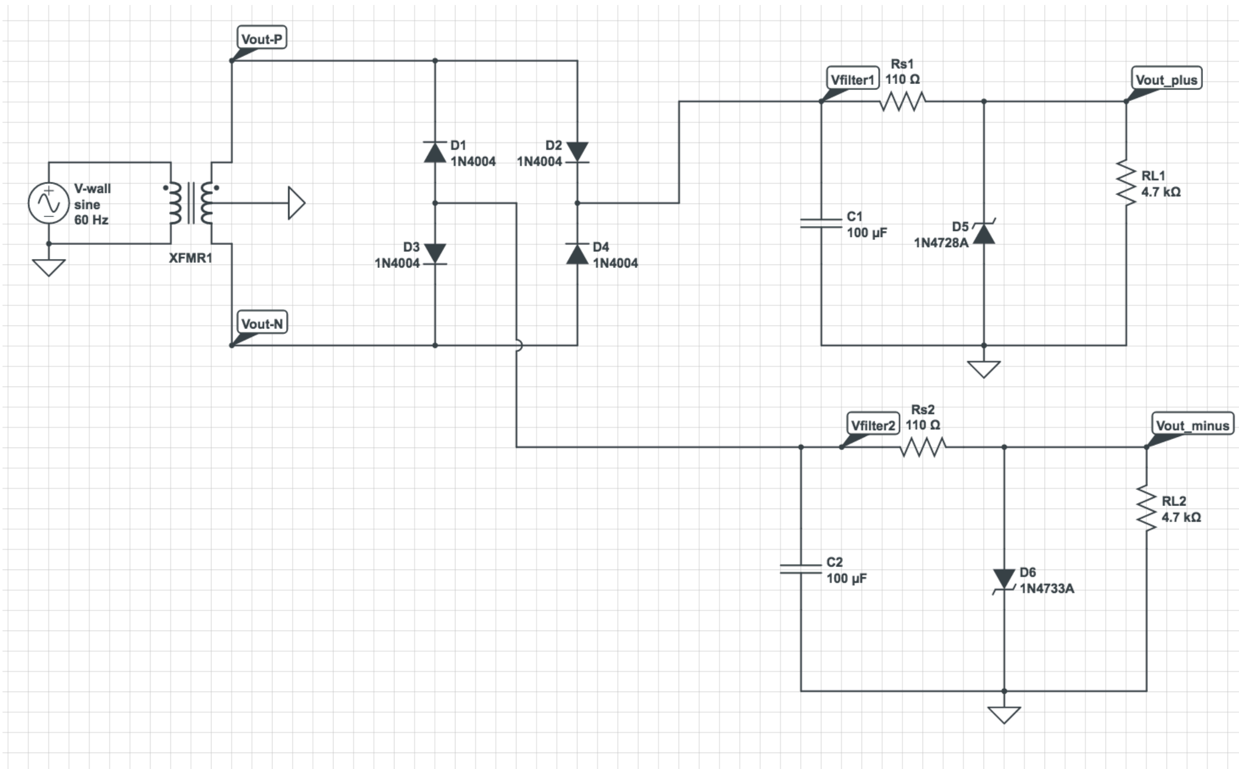
Voltage Regulator is the final component of the full power supply which is illustrated next.

Time-Domain Simulation:



Entire Power Supply:

Schematic:



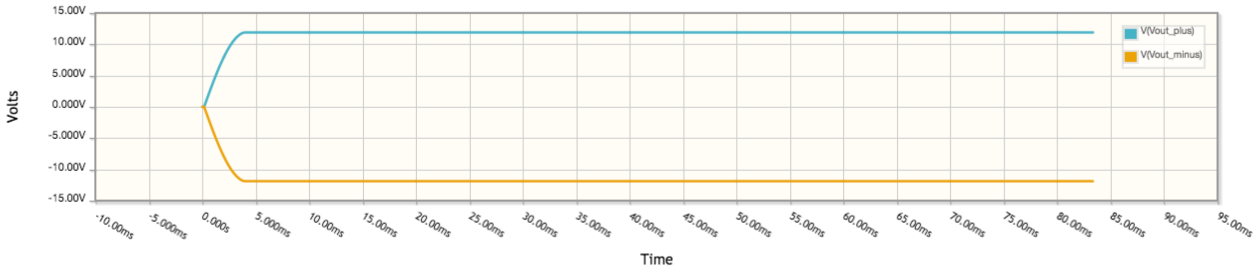
We tested the circuit illustrating the entire power supply above in the lab by inserting an LED (light-emitting diode) in series with the load resistors and ground. In the simulation, the LED points downwards in the positive output filter and upwards in the negative output filter.

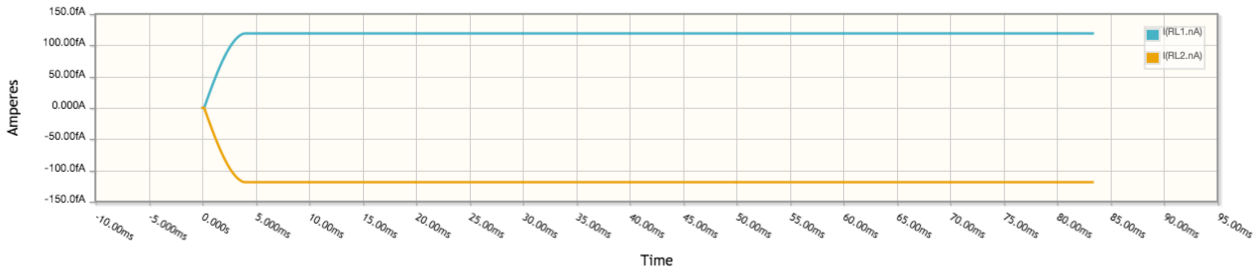
Time-Domain Simulation:

I was able to emulate a short-circuit and open-circuit by replacing RL1 and RL2 with extremely small and immensely large resistances (short & open) and I was thereby able to measure current through the resistor to supplement the voltage waveform graph.

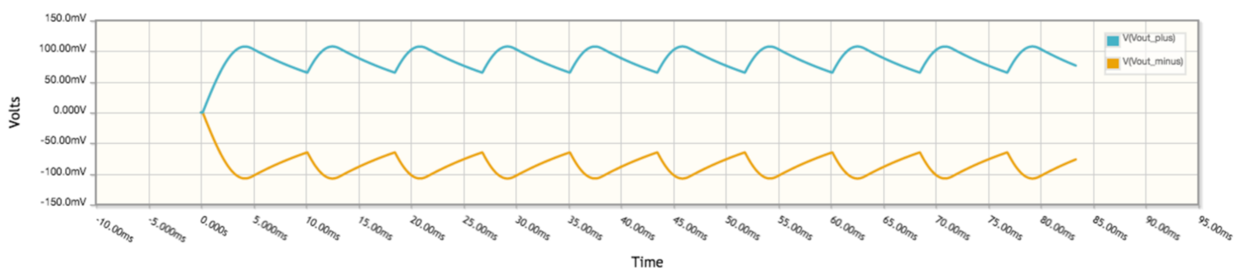
View next page for open circuit load and short circuit load voltage and current waveforms.

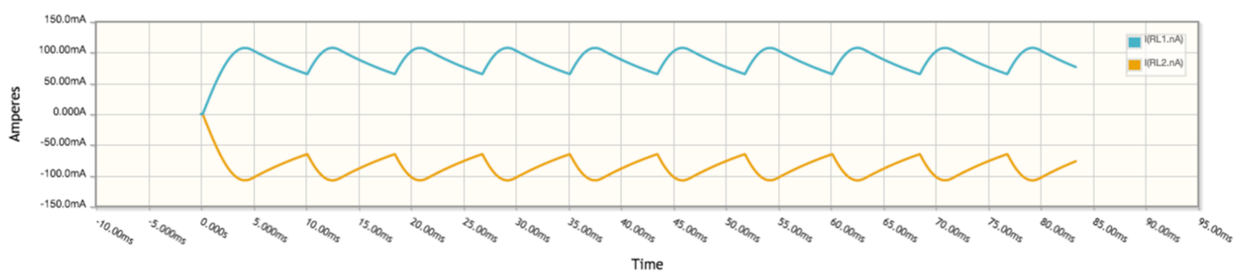
Open Circuit Load:





Short Circuit Load:





Experimental Results & Discussion

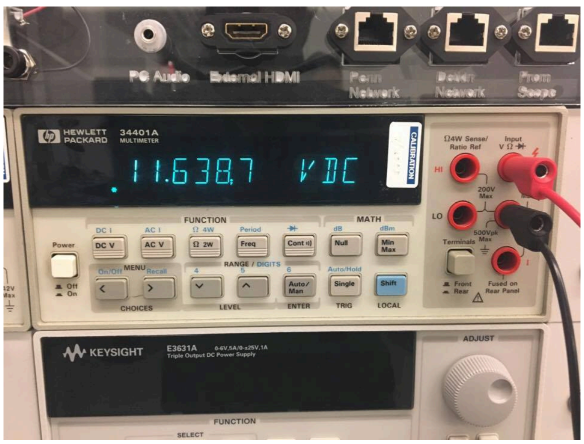
Experimental Setup and Procedure:

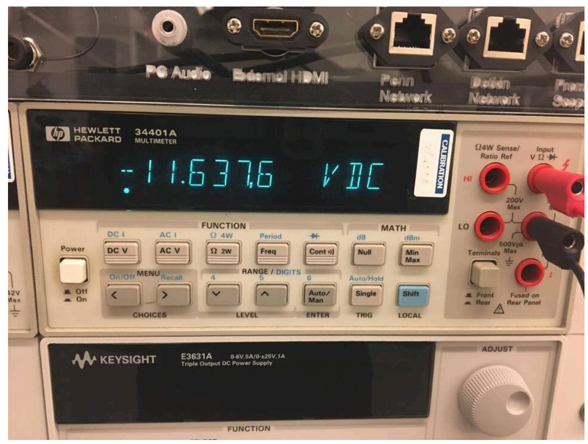
In this lab, we used the following equipment:

- Agilent MSO7034B Oscilloscope 300 MHz, 4 Analog channel + 16 Logic channel input MSO 7034B scope
- Digital Multimeter (including frequency counter) HP 34401A

- 500 MHz Agilent passive probe 10073D
- 1N4733A Zener Diodes ($V_Z = 12\ V; R_Z = 1\ \Omega$)
- 1N4004 Diodes
- 11.56V Transformer (center-tapped)
- Resistors (series and load)
- Breadboard & wires

In this laboratory experiment, we essentially recreated most of the prelab simulations on an oscilloscope. Ultimately we were successful in achieving a steady DC voltage near +12V and another that was approximately -12V, as captured by the digital multimeter below by reading the output voltages in series:





We began this lab by taking safety precautions, as neither of us had dealt with a voltage as high as one provided from the wall. The first step was to connect the transformer to the wall, and we were able to confirm that the transformer was operating how it should by testing it via the oscilloscope. Clearly, the voltage was now less than $115V_{RMS}$ as apparent in **Figure 1** of the results, which displays the voltage waveform of the positive and negative outputs following the center step transformer. A center step transformer has an additional wire leaving the center of the secondary coil, and we grounded this wire.

Our next task was to implement the full-wave rectifier—this was the first explicit move towards making the AC voltage into a DC one (essentially flattening the waveform at a fixed voltage of 12 V in our case). To do this, we inserted (Model: 1N4004) diodes into our circuit to only allow current to flow in the direction that the diode permits. Using this technique, we were able to build a half and subsequently a full wave rectifier such that the waveform transformed into one that never crossed the x-axis. This created two waveforms displayed in **Figure 2** of the results (green curve for the positive rectifier and blue curve for the negative rectifier).

Now that we had completed the full-wave rectifier, we were to now presented with the mission to create a filter that would smoothen voltage such that its ripple (peak-to-peak) voltage would hover around and within 2% of 12 V. To accomplish building a smoothing filter that performed at this efficiency, we had to test multiple capacitors and load resistors. The capacitor value that I had calculated in the prelab of 8.267 mF was unavailable to us in Detkin laboratory. The closest capacitor to that was a 4.4 mF capacitor, but unfortunately a 4.4 mF capacitor could only handle approximately 6V (as declared in its product information and evident when it blew up). Thus, we chose to use a 100 μF capacitor instead which could handle 50 V—more than sufficient to handle 12 V across it; by testing multiple capacitors of different capacitances in our circuit, we were able to gauge that the 100 μF capacitor provided minimal risk and optimal results. Furthermore, we began the implementation of the filter using a load resistance of 10 kΩ as guided in the helper documents and necessary in the Midterm Project Demonstration. We knew this resistance would work (smoothen the waveform to <2%) but it was not the lowest load resistance possible, as we were well within 2% evident in **Figure 4a** as 26 mV is far less than 254.6 mV and is only 0.217% of 12 V. Ultimately, we were able to go as low as 1.2 kΩ shown in **Figure 4c** and an intermediary step of 4.7 kΩ is shown in **Figure 4b**. As obvious from the results, we could have chosen a load resistance even lower, but for the interest of not potentially burning a portion of the circuit and satisfied with a 1.2 kΩ resistance, we chose to end our search for the lowest R_L there.

The final segment of the circuit was the voltage regulator, which consisted of a small series resistor R_S and a zener diode. We chose a zener diode that would only allow 12 V across it as that was desired output voltage that we wished to measure. We determined the R_S by testing multiple resistances to see which resulted in the smoothest line closest to 12 V, and this value was 110 Ω.

Our power supply was now complete and its waveform is represented in **Figure 5**—almost a flat line at +12.1 V and -12.1 V (~0.833% error based on oscilloscope reading!).

Experimental Results:

Figure 1 Transformer:

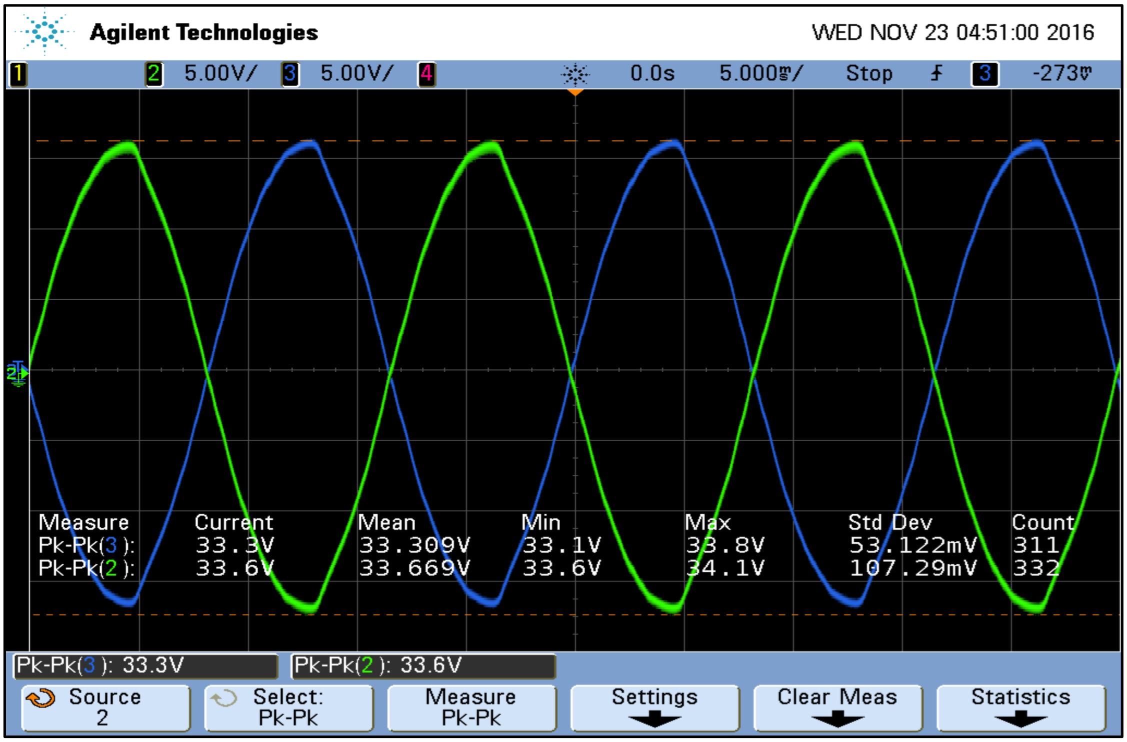


Figure 2 Full-Wave Rectifier:

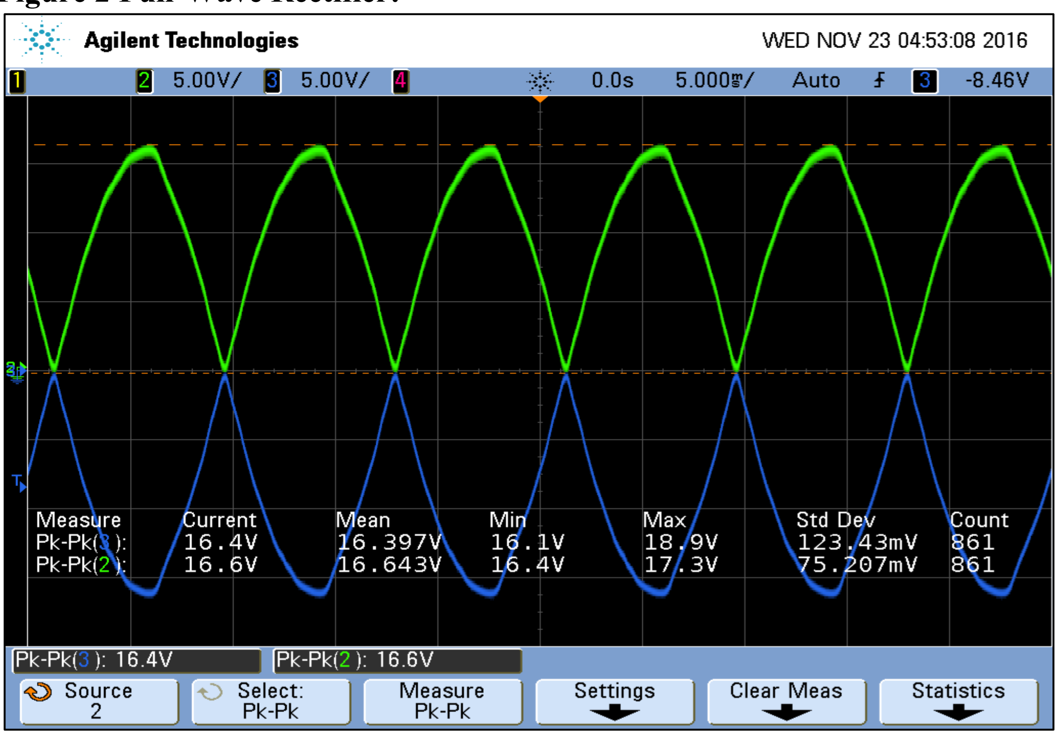


Figure 3 Smoothing Filter:

Figure 4a Voltage Regulator ($R_L = 10\ k\Omega$)**:**

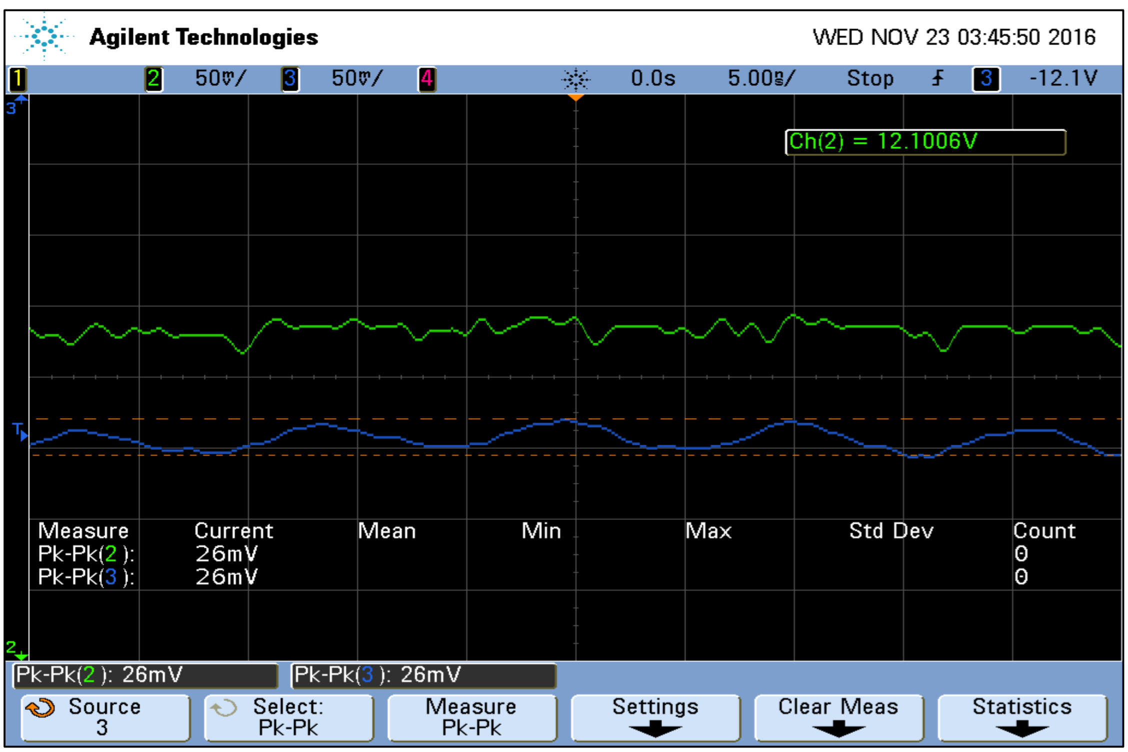


Figure 4b Voltage Regulator ($R_L = 4.7\ k\Omega$):

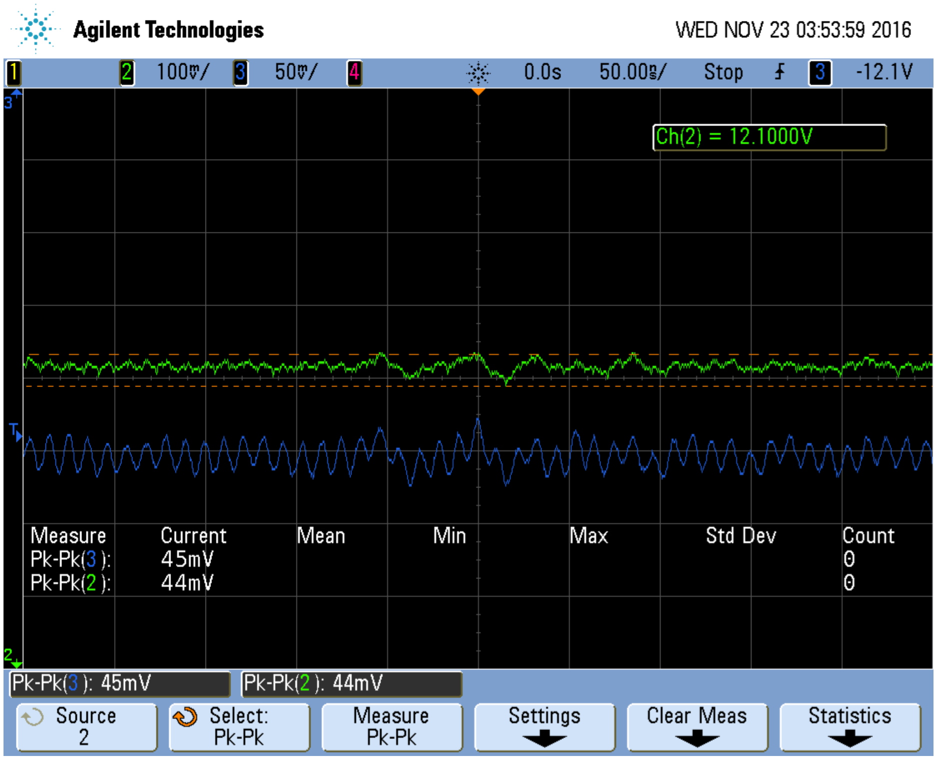


Figure 4c Voltage Regulator ($R_L = 1.2\ k\Omega$):

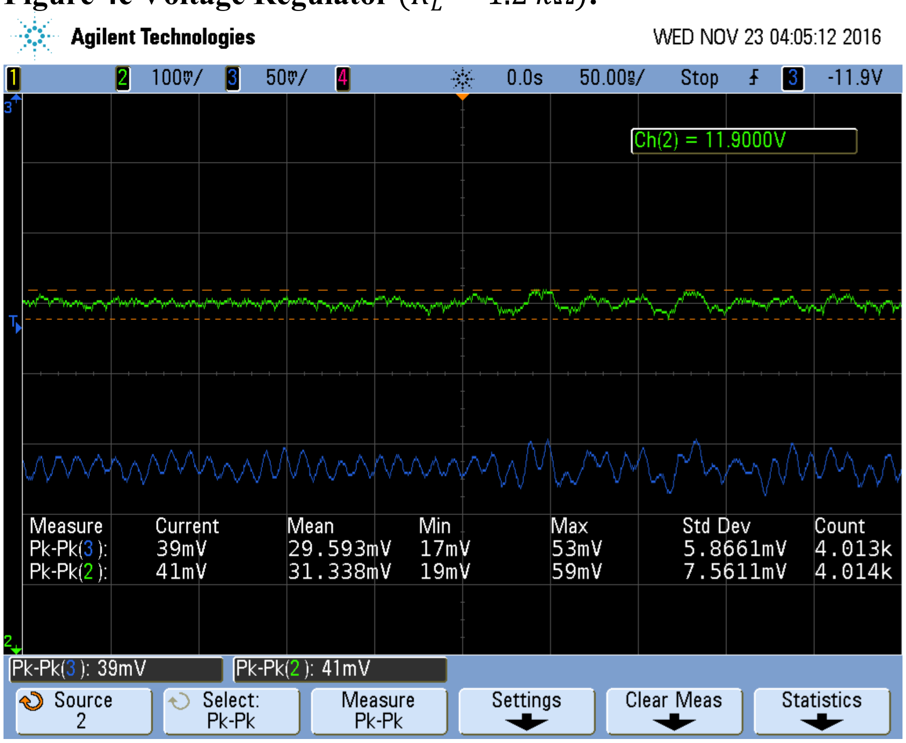
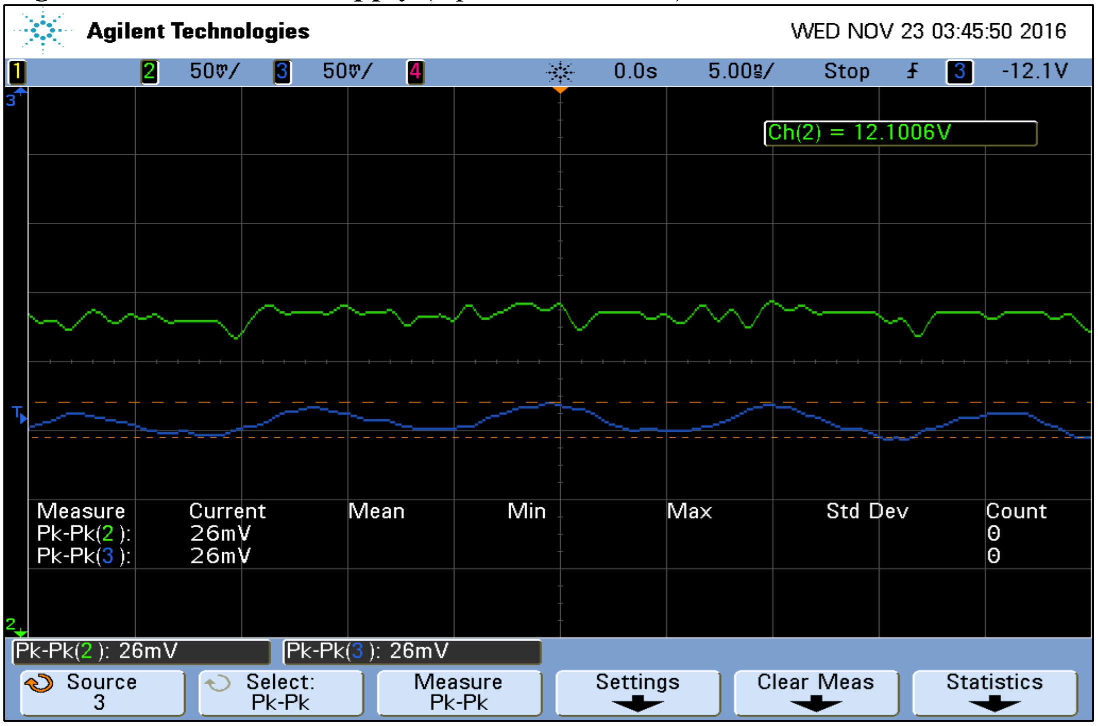


Figure 5 Entire Power Supply (Open-Circuit Load)**:**



Error Analysis:

Given the relatively complex nature of this lab, there was more room for error than usual. This was particularly due to the fact that it was very easy to mistakenly allow extremely high currents to travel through portions of the circuit—causing resistors to burn, capacitors to explode, and fuses (of the transformer) to break. These accidents were noticeable visually and audibly, but some other errors were less apparent and drastically skewed data: when the zener diode was corrupted, most elements operated smoothly except the final result was slightly off. Eventually, we realized that the zener diode was not unsusceptible to corruption and due to the physical structure of it, we had difficulty determining whether it was functional without testing it with due diligence. Furthermore, the transformer also provided a substantial amount of error in our results as evident in **Figure 1** of the experimental results, as the peak-to-peak voltage should be closer to 24 V than 33 V. This is likely due to the exact turn ratio of the transformer, which was not precisely our desired value given its results (granted the shape of the waveforms in **Figure 1** matched our objective). Furthermore, the voltage drop across each diode was given to be 0.6 V, which we used in calculating the desired capacitance, but this value for V_D is probably not entirely accurate. Fortunately, our ripple voltage was within 2% of 12 V, but the main factor that contributed for a greater ripple voltage was a low load resistance. The load resistance was also not always exactly what the color coding on it indicated, although we did our best to account for this by testing *every* resistor with the digital multimeter. Nevertheless, it is quite possible that the resistor's properties changed over the weeks that the lab was performed, especially with occasional high currents passing through them when we made mistakes building the circuit. Using the digital multimeter, we were also able to test our positive and negative output voltages and realized a -3% error between the desired final output voltage (±12V) and the acquired final voltage (±11.64V), which is solid given the complexity of the equipment and procedure. Our output voltage may be lower than the expected voltage because we underestimated certain voltage drops, particularly the voltage drops across the diodes in the rectifier.

Conclusion

Ultimately, we performed our lab quite marvelously in that we easily satisfied the ripple voltage conditions and were able to go to a pretty low load resistance (R_L), meaning that our circuit was efficiently constructed. Furthermore, we were successful in converting an AC voltage of approximately $115V_{rms}$ to a DC voltage of nearly ±12 V! Each component of the power supply worked well as evident with every figure in the experimental results, and we were able to accomplish the mission of creating a DC voltage given a transformer, capacitors, diodes, zener diodes, and resistors. We did not require any additional equipment to complete any component, including our full-wave rectifier, smoothing filters, and voltage regulator. Personally, this project's greatest takeaway is that the components in a circuit are not always reliable; values are not always what they are prescribed to be, so one must test components with due diligence to obtain optimal results. A correctly wired circuit and a working one can be two different things! Overall, this lab provided me with a better understanding of what goes on in practical, real-world electronics and how one can convert an AC voltage supply from the wall to a DC voltage supply.