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TO: JECO Director of Engineering

SUBJECT: Project 2: Power Supply with Linear Regulator

1. Statement of Purpose

The goal of the project was to design a power supply linear regulator that receives an input voltage from a transformer and outputs a voltage of 14 V at a sustained output current of 750 mA (within +/- 250 mA), and work over a range of 100 mA to 750 mA. The power supply had to have an input current limit of 1 A. The device had to turn off once it surpassed the 1 A threshold.

2. Theory and Design

2.1 Theory

Regulated power is essential for today's electronics since most modern devices require a constant supply voltage to operate correctly. In order to implement a regulated power supply, a regulator is needed, and in this case, a linear regulator.

The DC power supply is constructed of 5 parts: the AC voltage reduction, AC to DC conversion, filtering, regulation, and the load.

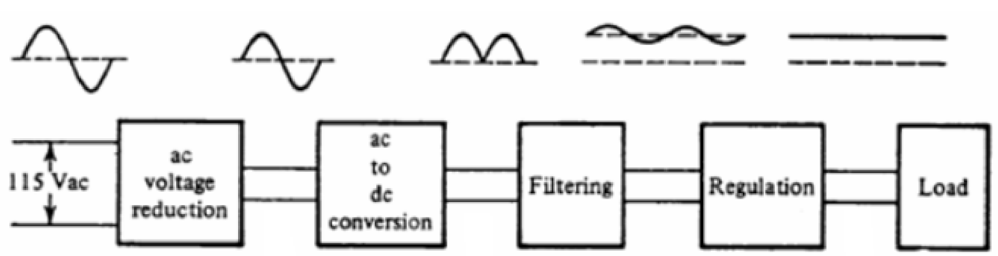

Figure 1: Linear Power Supply Block Diagram

The AC voltage reduction part of the circuit consists of a transformer. The relationship between the input and output voltage of the AC voltage reduction depends on the number of coil turns in the input and output coupled inductors, and is described by the following equation:

$$V_{out} = V_{in} \cdot \frac{N_{out}}{N_{in}} \tag{1}$$

Where V_{out} is the output voltage, V_{in} is the input voltage, N_{in} is the number of coil turns in the input inductor, and N_{out} is the number of coil turns in the output inductor.

For the AC to DC conversion a bridge rectifier was utilized, which is made up of 4 diodes configured in a diamond shape, and typically has a load resistor at their positive voltage pin (see Fig. A)

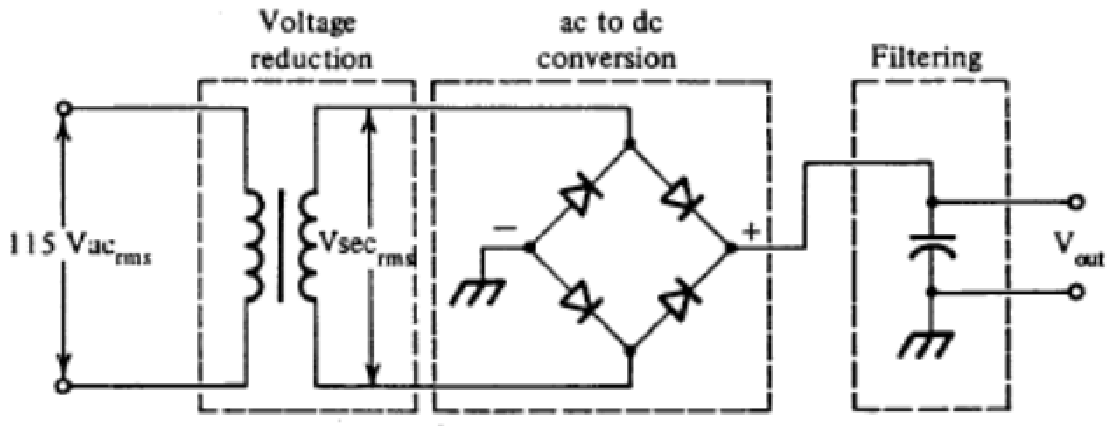

Figure 2: Transformer to Bridge Rectifier

In figure 2, it can be seen that the output of the transformer is inputted into two terminals of the bridge rectifier, while one terminal is grounded and the last terminal is inputted into a capacitor, which serves the purpose of filtering. The idea here is that the rectified output of the bridge rectifier (see figure 3) turns into something that looks like the output in figure 4 – see below.

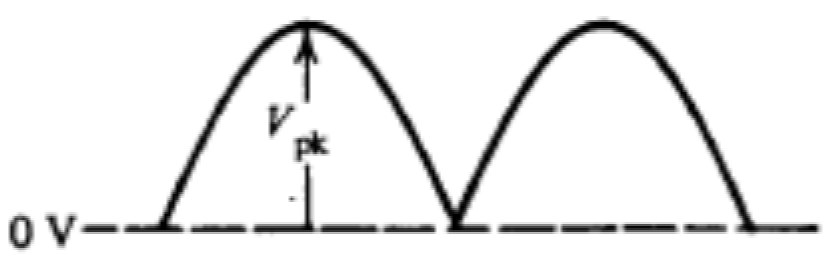

Figure 3: Output of the Bridge Rectifier

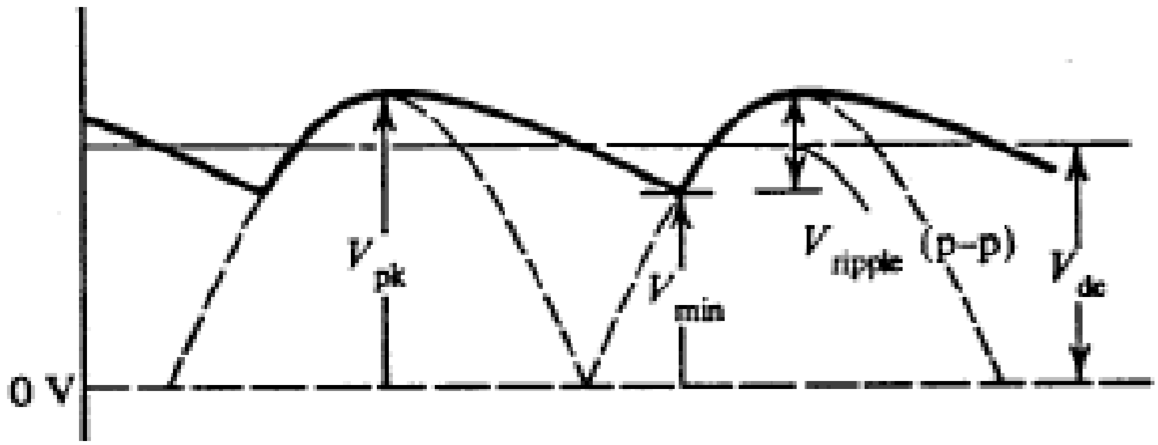

Figure 4: Filtered Output of the Bridge Rectifier

This filtered output that can be seen in figure 4 is almost DC. However, it has a slight ripple that will be talked about more in the design section; this ripple is expected. The regulator attempts to further stabilize this output into a constant DC value.

There are two types of voltage regulators: linear and switching regulators. In this case, a linear voltage regulator will be utilized. Linear regulators have active components in series with the load that regulates current flow; this is what allows the voltage across the load to remain constant. A key point of the linear regulator is that the output voltage must be constant invariant of the load current. There are many different ways to construct a linear regulator, but this project utilizes the LM723, which contains many parts of a voltage regulator as can be seen below in figure 5. Key parts of the regulator were the 0.68Ω power resistor and 1kΩ pass resistor. The purpose of the power resistor is to limit the maximum current experienced by the load and in general, used to limit current. The pass resistor is used in series with the transistor and the 723 and its main purpose is to limit current which provides feedback to the 723.

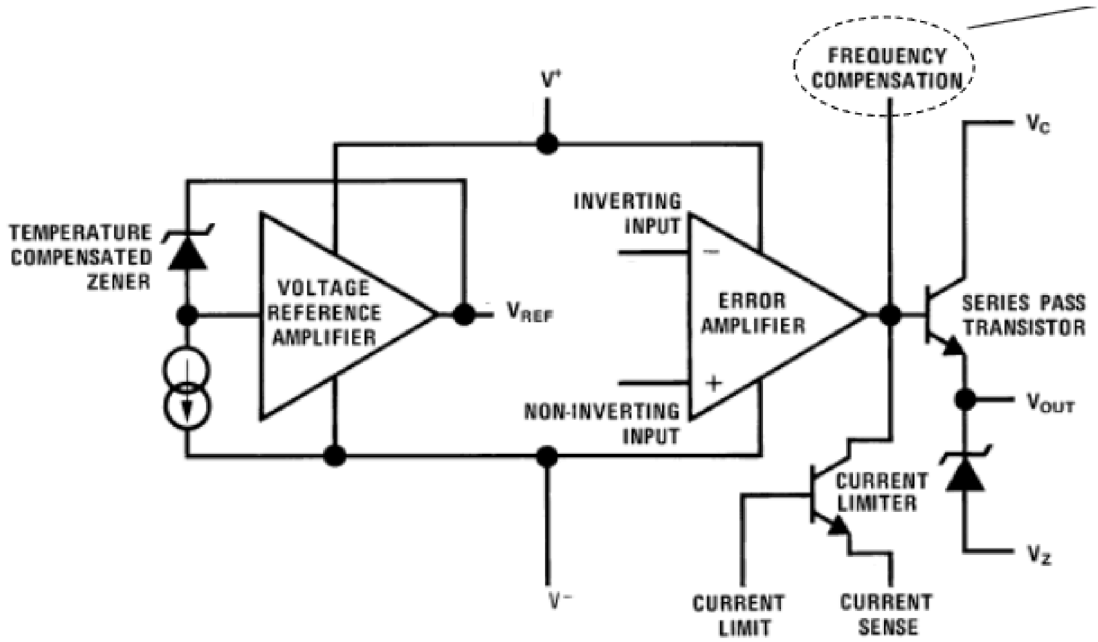

Figure 5: Internals of LM723

Ultimately, the regulator output when attached to a current load will be able to output $14V_{DC}$ between 100mA and 750mA and should not vary depending on load.

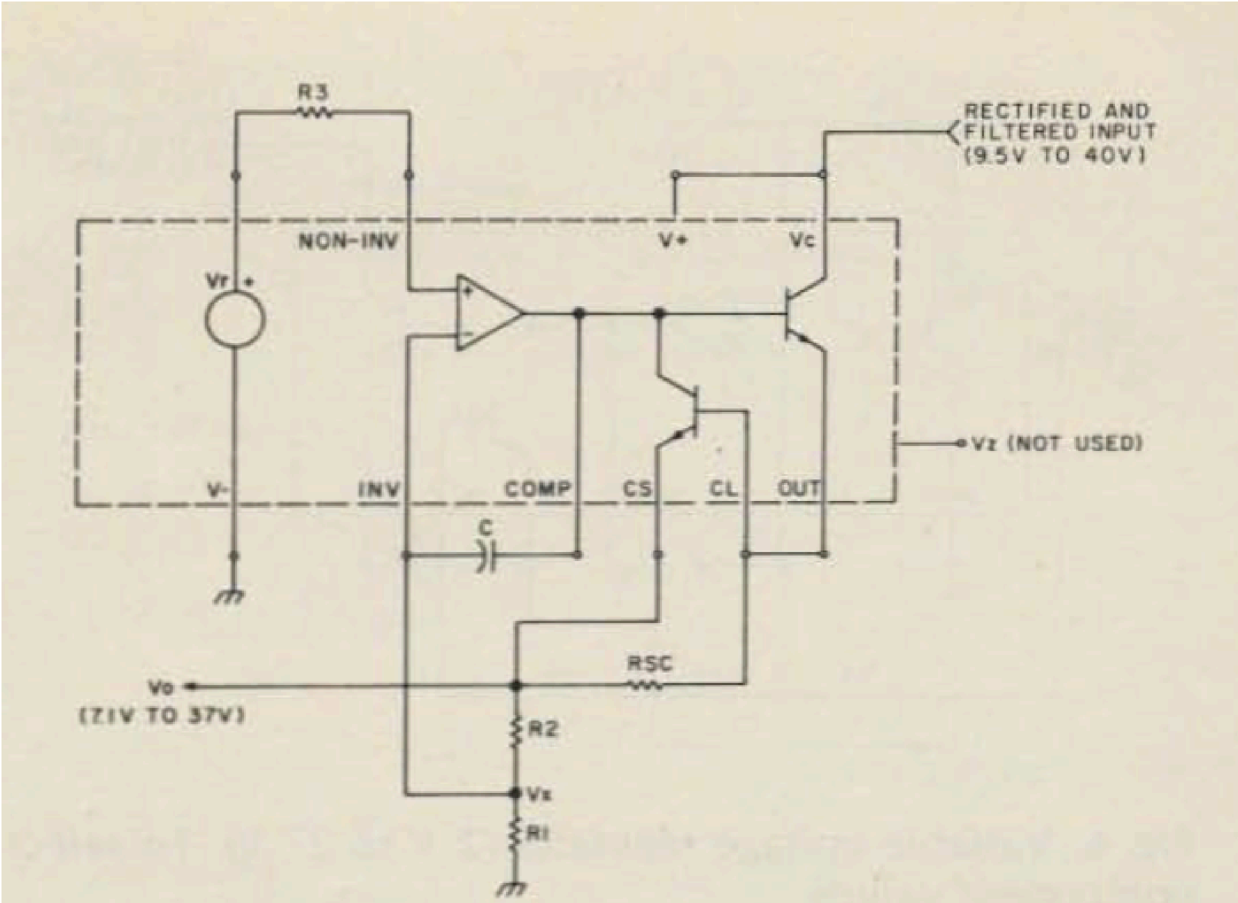

Figure 6: Regulator Design

In figure 6, the regulator design can be seen. A change made in the design is that a 1kΩ resistor was added between pin 11 and the capacitor banks, which helps a little with current limiting and allows a more stable voltage to get into the LM723. Other key components included the pass transistor and the power resistor. The point of the pass transistor, the tip31C, was to handle the majority of the power dissipation since the internal transistor of the chip couldn't handle it – its maximum current rating is 150mA. The power resistor is a series current limiting resistor chosen to limit the maximum current drawn by the load; when voltage exceeds the threshold set by the power resistor, the overcurrent protection gets activated. The resistors R_1 and R_2 formed a voltage divided to set the regulated output voltage, and R_3 existed as an optional resistor for feedback stability. The capacitor C existed also to ensure stability of the DC voltage and the operation of the regulator's feedback loop.

2.2 Design

The power supply starts with an input from the transformer brick provided in the lab.

Fig 7: Transformer Brick

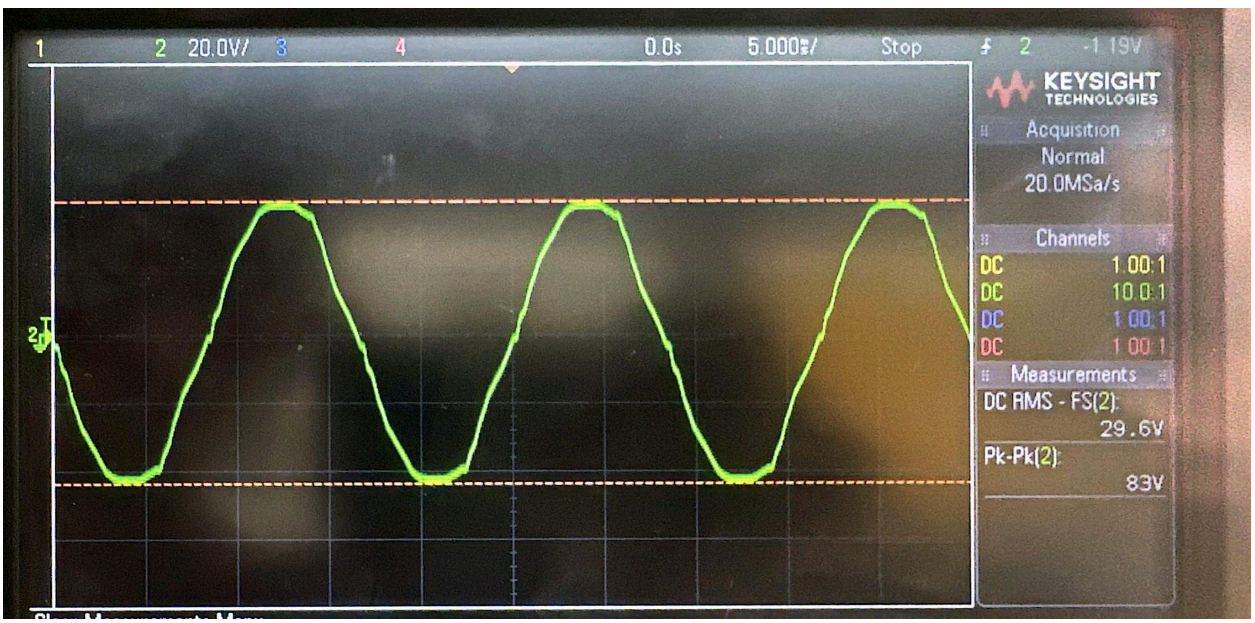

Fig 8: Output of Transformer

The transformer above in figure 7 provided a voltage of $83V_{pp}$ and a V_{rms} of 29.6 V (seen in figure 8); the output of the brick is the secondary winding of the transformer. The top tap of the brick is the input on one of the middle legs of the bridge rectifier, while the bottom tap of the transformer is the input into the other middle leg of the bridge rectifier.

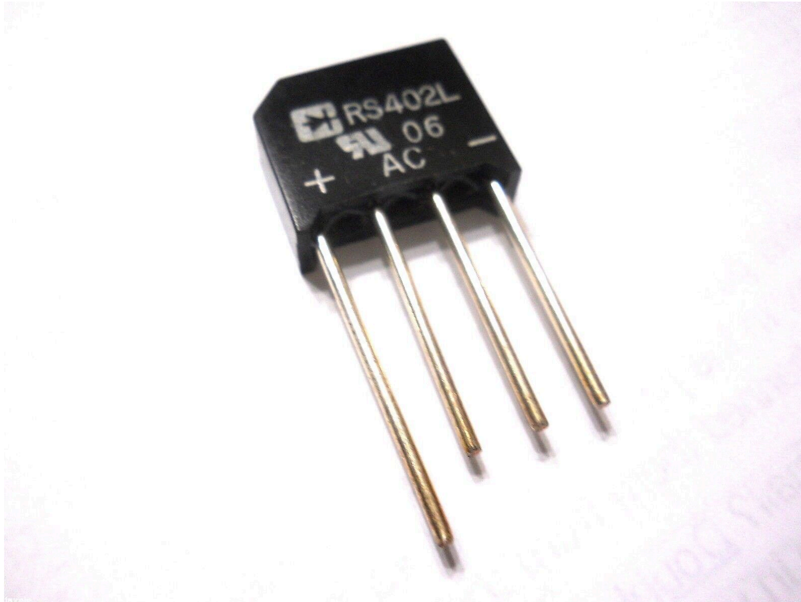

Fig 9: RS402L Bridge Rectifier

Above, in figure 9, the mentioned bridge rectifier can be seen. The rectifier, which along with the output capacitor, creates a rectified output with a small ripple. To minimize this ripple, we choose a capacitive value of 2000µF based on the equation below.

$$V_{min} = V_{pk} - \frac{I_{DC}}{fC} \tag{1}$$

In this equation, the DC current should vary from 100 to 750 mA. The frequency is set to be 120 Hz for the full wave. However, the equation provided is a light load approximation, where the ripple voltage is less than 10% of the output DC voltage. This ripple must be small so that the output can be approximated as DC.

Without diving too deep into the math, the peak voltage was around 41.5V considering figure x, and considering the maximum current of 750mA, a capacitance of 2000µF would result in a minimum voltage of 38.38V.

$$V_{pk} - V_{min} = V_{ripple(p-p)} \tag{2}$$

An important result is having the ripple voltage be less than 10% of the minimum voltage. The ripple voltage ends up being 3.12V, which is below the required threshold. This requirement ensures a stable input into the next stage of the power supply, which is the voltage regulator. If the ripple is too high, the input voltage could drop below a regulator threshold and cause unpredictable behavior and fluctuations.

The output of the bridge rectifier (the + pin as seen on figure 9) is then fed into the voltage regulator. Since the output needs to be a specific DC value of 14V, the LM723 voltage regulator was used; it provides an adjustable output voltage in the range of 7.1V to 37V. By choosing appropriate resistor values, it is possible to manipulate the output to a desired voltage.

There are five components that must be selected for the chosen setup from the "Many Talented 723" article that can be seen cited below: R_1,R_2,R_3,R_{sc}, and C. By choosing V_o to be 14V, assuming V_r to be 7.1 V (an internal chip voltage), and setting the base current I_b between 0.1 and 5mA (choose 1mA), the following equations can be used

$$R_1 = \frac{V_R}{I_b} \tag{3}$$

$$R_2 = \frac{V_o - V_R}{I_b} \tag{4}$$

$$R_3 = \frac{R_1 R_2}{(R_1 + R_2)} \tag{5}$$

C was set to 470pF (choose a value between 100 and 500pF) and R_{sc} was set to 0.68Ω (manual called for 0.65Ω). In the next section, a better visual of the setup can be seen with a visual of the power supply's circuit diagram.

3. Implementation

3.1 <u>Board Design and Implementation</u>

The implementation of the power supply can be seen below.

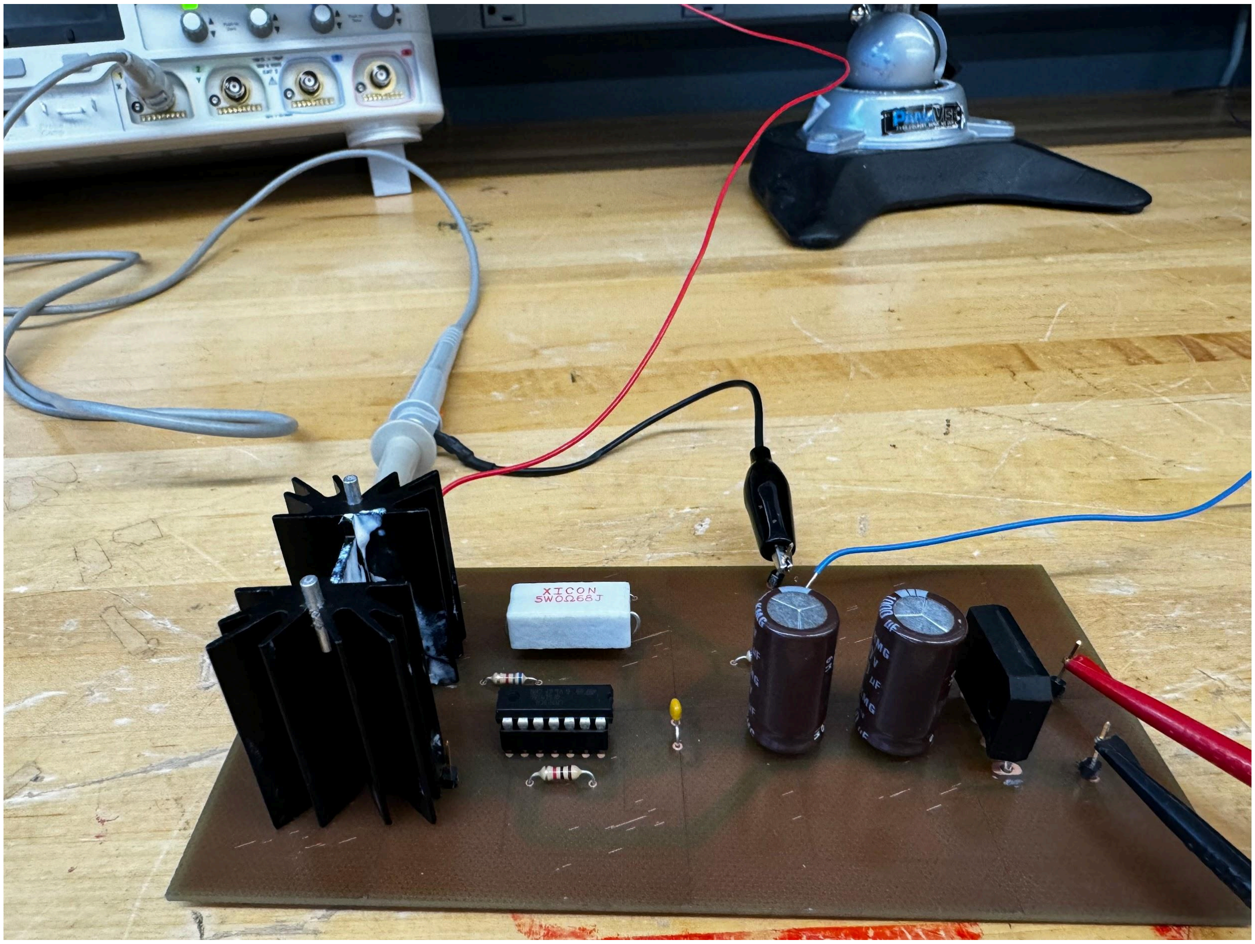

Figure 10: Implemented Power Supply PCB

Above in figure 10, the implemented 14V power supply can be seen. The initial design was taken from the "Many Talented 723" article as stated above. By choosing V_o to be 14V, assuming V_r to be 7.1 V and setting I_b to 1mA, values were calculated. R_1 was found to be 6.87kΩ, R_2 to be 7.15kΩ, and R_3 to be 3.5kΩ. The value of the power resistor and capacitor for the regulator setup was given in the article.

However, in practice, some challenges were faced. The design for the filter capacitor had to be changed to consist of two, 1000uF capacitors instead of one, 2000uF capacitor was not available at the time. In theory this should not make a difference, but in practice, additional wiring can result in signal loss and use space unnecessarily. Another challenge was determining the resistor values R1, R2, and R3. As noted above, the values were determined using the article but during testing, the output voltage did not stay within the 250mV tolerance required. As a result, additional testing was done by adjusting the values of the resistors until an output voltage within tolerance was achieved. Final resistor values ended up having $R_1 = R_2 = R_3 = 6.8k\Omega$.

Another challenge was the TIP31C transistor burning up during testing. The power supply functioned as expected during the 0.1A, 0.25A, 0.5A, 0.75A load currents but for the 1A load current, the output voltage initially drops to near zero as expected, but jumps to 28V after a few seconds. When attempting to change the load current back to less than 1A, the output voltage did not revert back to 14V. After retesting the board multiple times with new components, the issue seemed to stem from the transistor having inadequate heat dissipation. Using the top and bottom taps of the transformer instead of the top and middle taps likely caused too much power dissipation in the transistor when pushed to 1A. Some theories for the reason why is that the breadboard may have had better cooling because of better airflow, and long wires used on the breadboard could have had more resistance and slightly decreased the current.

Below is the engineering drawing of the linear voltage regulator:

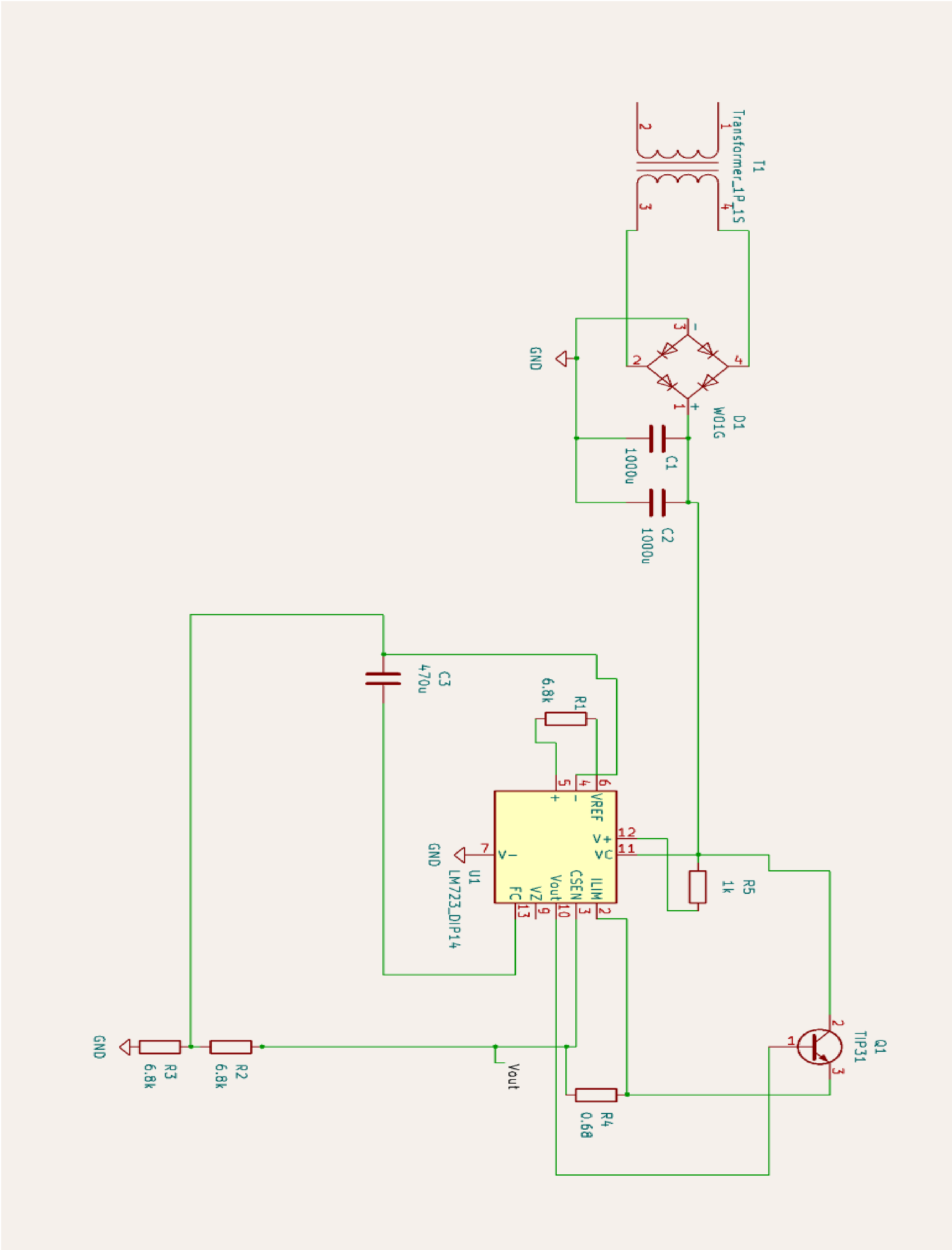

Figure 11: Engineering Circuit Diagram

4. Laboratory Circuit Evaluation

4.1 Configuration

The following equipment was used to obtain the necessary results:

- Oscilloscope
- Oscilloscope Probe (1)
- Banana Cables (2)
- Wires (2)
- Electronic Load

The red and blue cables were attached to each middle pin of the bridge rectifier, the oscilloscope probe was attached to the output to measure DC voltage. The blue wire went from the electronic load to ground, and the red wire went from the electronic load to the output.

The purpose of the electronic load was to supply a load current through the regulator.
Below, the test setup as well as the block diagram for the test setup can be seen.

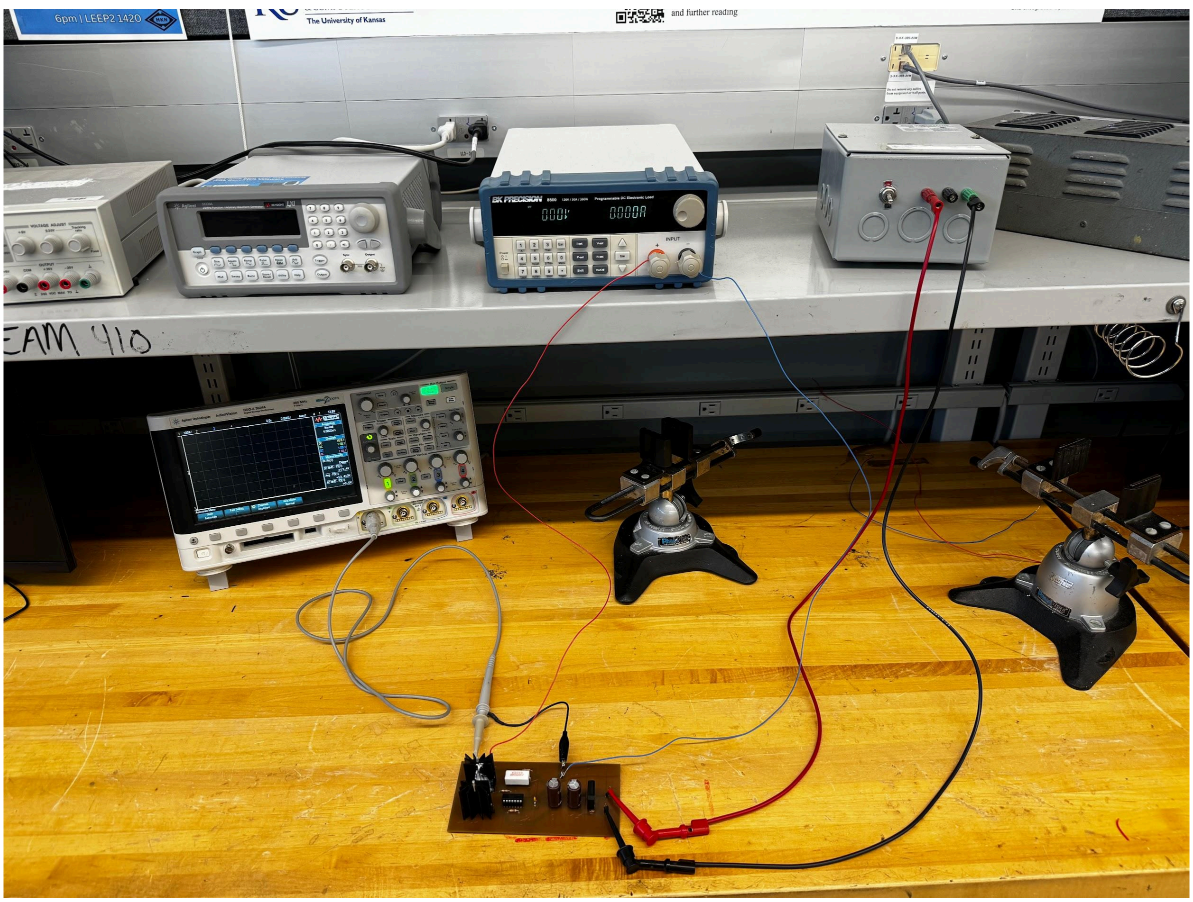

Figure 12: Test Equipment Setup for Evaluating Linear Power Supply

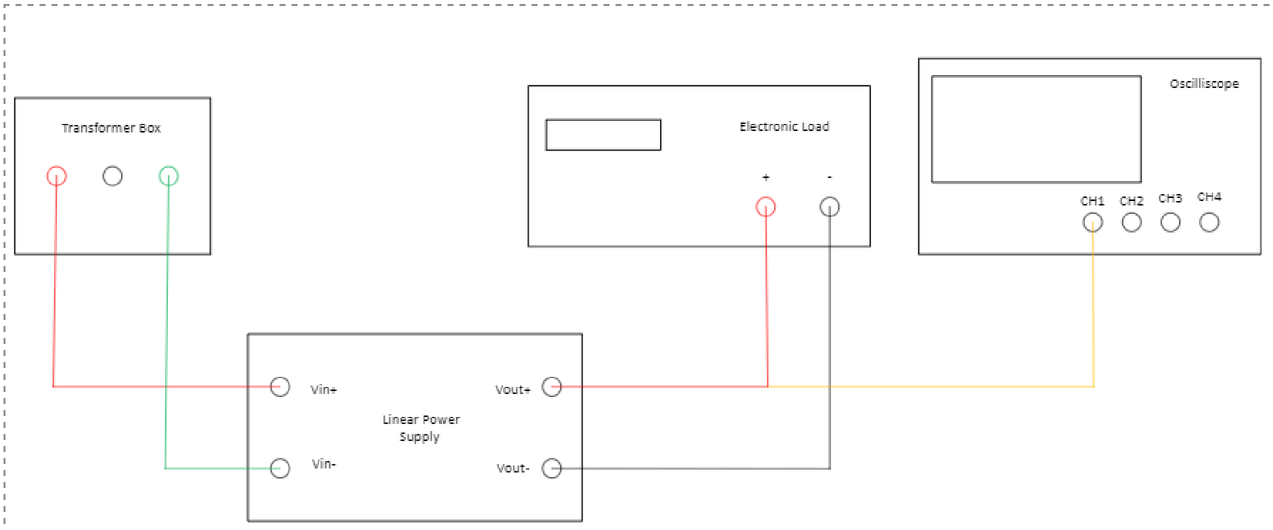

Figure 13: Test Equipment Setup Diagram

4.2 Procedure

The circuit had to meet three primary objectives. The first objective was for the power supply to be capable of providing 750 mA in output load current at 14V. The second objective was to meet the specified output voltage of 14V within a +/— 250 mV tolerance over a range of 100 mA to 750 mA. Lastly, the regulator should have been designed with over-current protection that restricts the maximum current to 1A. After making the necessary connections as shown in figure 11, the output voltage was measured using an oscilloscope probe connected to the output of the power supply and ground. The positive terminal of the electronic load connected to the output of the power supply and the negative terminal to the negative voltage output of the power supply (ground). Controlling the input current was done using the electronic load. The top tap of the transformer box supplied the 83V AC (29.8 V_{rms}) voltage and was connected using banana cables to the positive voltage input of the bridge rectifier and the bottom tap was connected to the negative voltage input of the rectifier.

For all objectives, the measurement is made at the output. By observing the voltage seen at the programmable load, it is possible to view that the output voltage is within the tolerance. The output current and overcurrent protection can also be viewed at the programmable load. Ideally, the voltage drops to around 0 when the current gets close to 1 A.

5. Evaluation of Test Data

5.1 Data

Questions Provided:

Provide a plot of the output voltage versus load current from low-load (~50 mA) to maximum load (~1 A). Make sure this plot demonstrates the current limiting capability of

the power supply. Accompanying text describing the results and their meaning or significance is required

A plot of the load current vs the output voltage can be seen below. Current limiting can be seen at 1A since the output voltage drops to 0.03V. The load current 0.25A instead of 0.1A was used for the first current to have an even split of current.

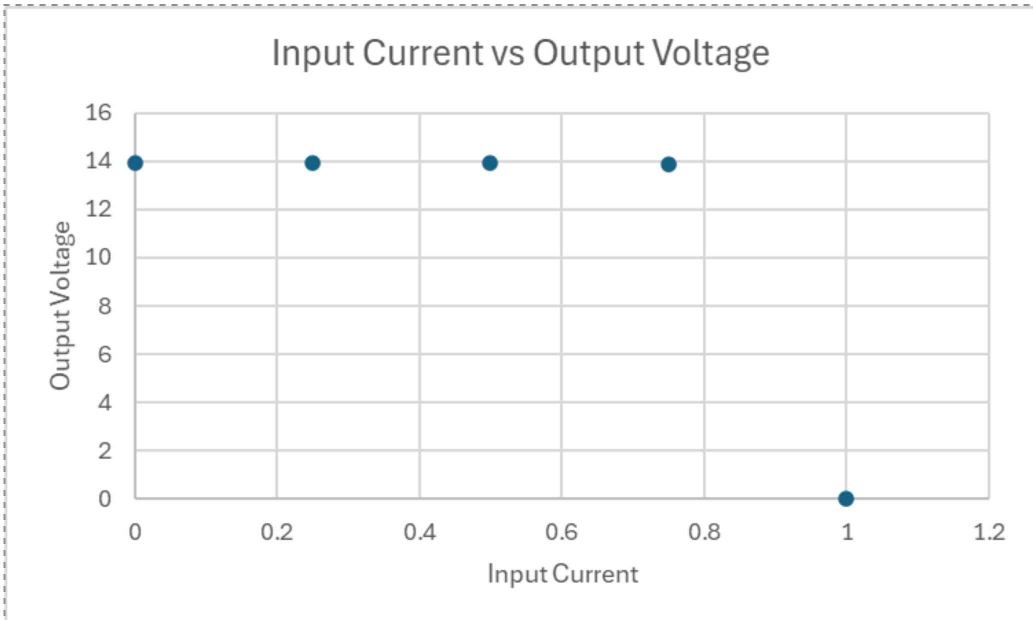

Figure 14: Load Current vs Output Voltage measurements

Input Voltage	Output Voltage (e-load) [V]	Load Current [A]
28	13.95	0
28	13.92	0.25
28	13.91	0.5
28	13.89	0.75
28	0.03	1

Table 1: Data for figure 14

Using your plot of the output voltage versus load current, determine the internal resistance of your power supply:

The internal resistance was calculated to be 0.08Ω using the equation shown below and taking the average of the values at each load current.

$$(V^{OC}_{out} - V_{out})/I = R_{internal} \quad (6)$$

$$(13.95 - 13.91)/0.5 = 0.08\Omega$$

For your specific circuit, determine the maximum heat sink thermal resistance allowable to protect your pass transistor from overheating.

The maximum allowable heat sink thermal resistance can be found using the equation below.

$$\theta_{sa} = \theta_{ja} - \theta_{jc} - \theta_{cs} \quad (7)$$

θ_{ja} is the thermal resistance from sink to ambient, θ_{jc} is the thermal resistance of the transistor from case to sink, and θ_{jc} is the thermal resistance from the junction to the case. θ_{ja} is defined as:

$$\theta_{ja} = \frac{T_j - T_a}{P_D} \quad (8)$$

Therefore,

$$\theta_{sa} = \frac{150-25}{30} - 3.125 - 0 = 1.04$$

The maximum heat sink thermal resistance for our circuit is 1.04. The values used in this calculation were taken from the data sheet for the transistor and maximum power dissipated was assumed to be 30W.

Determine the load regulation K, as a percentage, according to the following formula

$$K = \frac{V_{RL(max)} - V_{RL(min)}}{V_{RL(min)}} \times 100\% \quad (9)$$

$$K = \frac{13.95-13.89}{13.89} \times 100\%$$

K = 0.431965 %

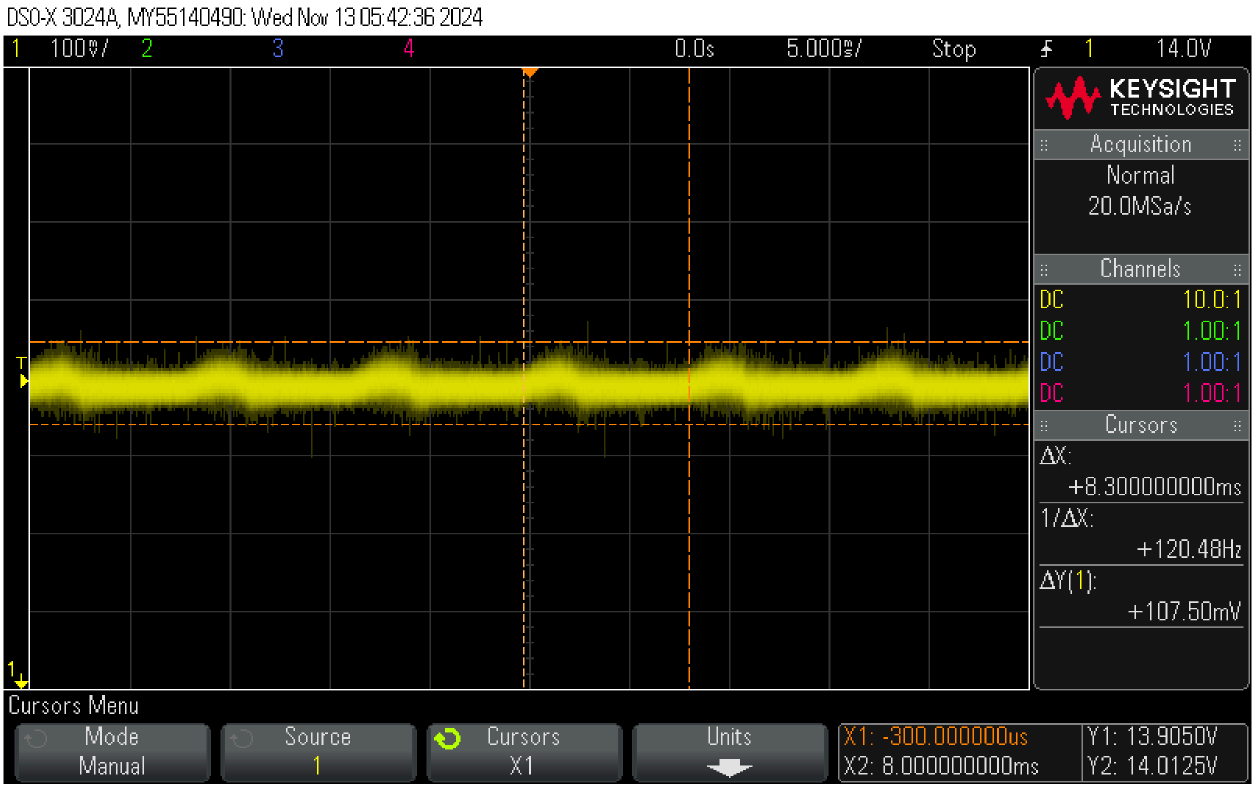

Figure 14: Ripple characterization in oscilloscope

The ripple of our circuit has a dominant frequency of 120.48 Hz, and has a ripple peak-to-peak voltage of 107.5 mV, as observed in Figure 14. The ripple waveform appears to be sinusoidal.

5.2 Interpretation

The output voltage for the load showed the measured value from the constructed circuit. The values shown match the expected values for the circuit that was designed. All values collected were within ±0.25V of the expected output, which meets the requirements for the power supply. The circuit successfully limited the voltage at 1 A and made the output voltage go to zero as required.

The internal resistance of the supply was found to be 0.08 Ω by averaging the resistance values that were calculated using ohm's law for each load current. The small internal resistance shows that there is a small amount of loss through the circuit. The maximum allowable heat sink thermal resistance was found to be 1.04 °C. The circuit had an issue where the pass transistor was overheating relatively quickly at 1 A. The only way to get the circuit to function at 1 A was to slowly turn up the load current, but the transistor still did not last long, maybe hinting at a thermal runaway issue for the pass transistor.

The issue was determined to be from overheating, which is shown by the maximum heat sink thermal resistance to be true. The heat sink has a thermal resistance of 3.7, which is more than twice the maximum allowable level. If a different heat sink was chosen for the circuit the issue caused by overheating would be solved. Other potential reasons for the overheating could have been bad thermal contact between the transistor and heat sink or cold solder joints.

The load regulation was found to be 0.43%, showing that the regulation is able to keep a constant voltage due to changes in load current. While the ideal value for the load regulation would be 0%, this result would be acceptable for almost any practical application. The ripple of our circuit has a dominant frequency of 120.48 Hz, and has a ripple peak-to-peak voltage of 107.5 mV. The ripple waveform appears to be sinusoidal. Again, while the ideal scenario here would have been zero ripple, this small ripple is typical for a practical design.

5.3 Conclusions

Overall, the 14 V power supply system demonstrated effective operation within the specified parameters. The circuit was able to provide a stable output voltage, consistently maintaining 14 +/-0.25 V for different current demands, which met the design requirements.

However, we found a limitation during the testing phase for the PCB circuit. Although the circuit worked perfectly in the breadboard, when assembling the PCB, our circuit would only work up to currents around 0.9 A, but that's around when the pass transistor started burning up. To address this, a potential improvement would be to either incorporate better heat dissipation methods, such as better heat sinks, by choosing circuit components that have better power tolerance (especially for the transistor case), or by choosing circuit components that drew off greater amounts of heat before the input power arrived at the transistor, letting the circuit perform its current limiting feature.

Another aspect to consider for improvement is the overall efficiency of the power conversion process. While the system performed well, losses in the conversion process were evident, particularly at higher currents. This could be improved by using more efficient components, optimizing the system's performance.

All in all, while the power supply functioned as intended, incorporating improvements in thermal management and efficiency could significantly enhance its performance and reliability to produce a final circuit version that complies with the initially current limiter request.

6. References

[1] Prescott, Glenn. The Many-Talented 723.

[2] "LM723." *LM723 Data Sheet, Product Information and Support | TI.Com*

[3] *RS402L Rectron | Mouser.Com*

[4] “Tip31c.” *DigiKey Electronics*, *DigiKey.com*