AC to DC Boost Converter Design Project

EE 331

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1. *Project Outline*

The purpose of this final design project was to test our knowledge and understanding of course material presented to us over the duration of EE 331, Devices and Circuits I. The overall function of our final design is to accept a ±7.5VAC(rms) voltage from a transformer and output a variable DC voltage between +10V to +20V based on the minimum and maximum resistance values of a 10 kΩ potentiometer. The specifications for this design includes:

1. Input voltage of ±7.5 VAC, obtained from the laboratory transformer.
2. Continuously adjustable output voltage of +10.0 VDC to +20.0 VDC which can deliver from 0.0 to 1.0 mA of current to a load at any of the above voltage.
3. Output voltage must be adjustable by means of a single potentiometer in the circuit.
4. The circuit must employ a rectifier and a capacitive filter which establish an unregulated DC voltage of approximately 10 V with a ripple of less than 1.0 V.
5. The circuit must employ a boost topology comprising a transistor switched inductor and a catch diode that feeds an output capacitor. Each of these four parts must operate within their rated limits.
6. The transistor switch must be clocked by an on-board oscillator with a frequency in the range of 10 kHz to 100 kHz.
7. The DC output voltage of the converter must have less than 100 mV of ripple

We began our project design by creating a block diagram that denoted every specification requirement, every input feed, and every output feed for each of the described parts above: A Full-Wave Bridge Rectifier, A Boost Topology, A 555 Timer (clock), and a Voltage Divider.

2. *The Block Diagram*

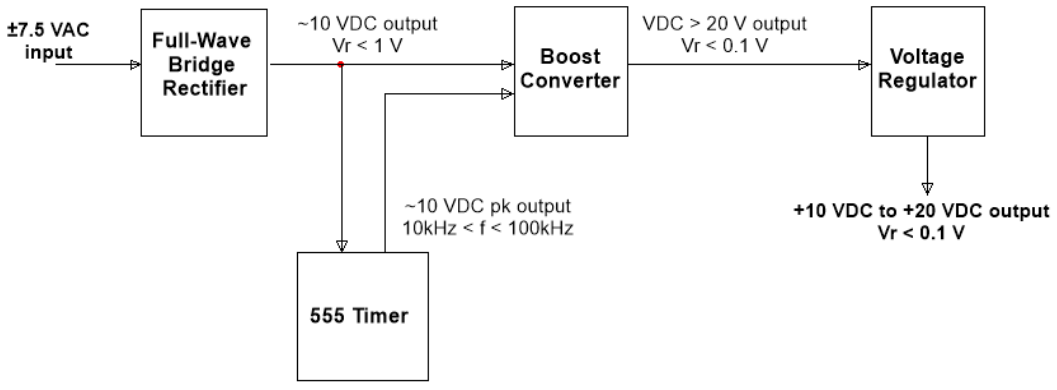

Figure 2.1. The Block Diagram with Specification Requirements

Figure 2.1 above is the block diagram that outlines the project's key features. This helped us begin the design process. We started our design by evaluating the specification requirements for the full-wave bridge rectifier.

3. Design Components

3.1 The Full-Wave Bridge Rectifier

The input, a ±7.5VAC(rms) transformer, is the initial signal into our bridge rectifier which then outputs roughly 10VDC with Vr < 1V. We needed to design an RC load across the diodes to hold a relatively constant peak voltage of about 10VDC. The output voltage of the bridge rectifier did not hold very specific requirements, just a rough requirement of around 10 VDC. Therefore, the majority of our focus was meeting the requirement of the ripple voltage, Vr < 1V. Given Equation 1:

$$V_{ripple} = \quad (V_P - 2V_{ON})T / (2R_L C) \tag{1}$$

we were able to calculate the needed capacitance and resistance to achieve a small enough ripple voltage. Initially, we stated R_L to be 1MΩ and calculated the required capacitance to see a ripple voltage of less than 1 V. Our given variable values included $V_P = 7.5\ \sqrt{2} = 10.6$ V, $V_{ON} = 1$ V, and T = 1 / 60 Hz. We calculated a capacitance of 0.4 μF that gave us a ripple voltage of Vr ≅ 0.8 V. However, we quickly realized the ripple voltage is inversely related to the capacitance. Ignoring the values of V_P, V_{ON}, and T, we were able to purchase a fairly large capacitor from the EE Store that held a capacitance of 4700 μF. In parallel with the 1 MΩ resistor, the output voltage and ripple voltage is recorded below.

Bridge Rectifier Output Voltage:	8.32 VDC
Bridge Rectifier Ripple Voltage:	17.5 mV

The final design schematic of our rectifier is seen below in Figure 3.1.1.

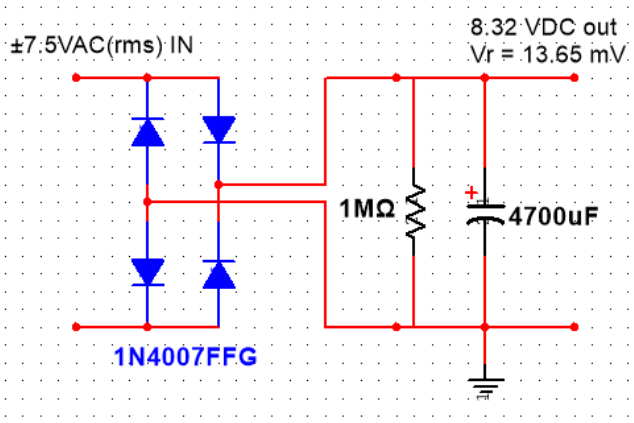

Figure 3.1.1. Full-Wave Bridge Rectifier Schematic

Under no load the output voltage would ideally stay at a constant, high VDC value. This is because the capacitor has no discharge path, leaving it to hold its peak value. However, the inclusion of a load resistance introduces the issue of a voltage drop across V_{OUT} of the bridge rectifier. Initially in this lab we measured this large voltage drop across the output. However, during this stage of our design we had limited capacitance. Our capacitance was roughly 0.4μF, a value that was far too low for our desired load resistance. Once we replaced this capacitance with the larger 4700μF, the capacitor held enough charge to maintain a output voltage of 8.32VDC without seeing a drop with the introduction of a resistive load.

Note that the output voltage varies with changing transformers. Transformers in lab were measured to vary from 7.1 VAC (rms) to 7.8 VAC (rms). The larger the VAC, the higher the VDC output of our bridge rectifier. Also, the Pk-Pk value of our output waveform does not represent our ripple voltage output of our bridge rectifier. The rectifier outputs varying static signals that increase the oscilloscope measurement of our pk-pk. The waveform of the ripple voltage is seen below in Figure 3.1.2. Note the spikes in voltage (noise) caused by the inaccuracy of the oscilloscope.

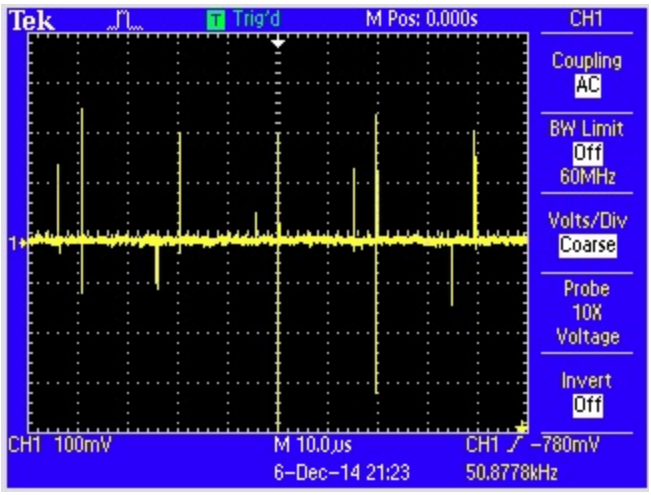

Figure 3.1.2: The Bridge Rectifier Ripple Voltage Waveform

The true value of our ripple voltage is measured by the multimeter in lab. This was calculated to be 17.5 mV, as previously stated.

Once we designed, simulated, and successfully constructed our bridge rectifier, we focused on the 555 timer and its specification requirements.

3.2 The 555 Timer

The function of the 555 Timer is to allow the 2N7000 MOSFET inside the Boost Converter (see Section *The Boost Converter*) to switch on/off. When the timer outputs a voltage to the gate of the MOSFET, it closes the switch allowing current to pass through the transistor. Once the gate voltage reaches 0 V (when the clock is "off"), the switch opens, restricting current flow. This on/off cycle repeats at a constant frequency of our choosing. The frequency requirements for this clock were unrestricting; we needed to make sure our frequency ranged between 10 kHz to 100 kHz. Therefore, our main focus was implementing the correct duty cycle. The duty cycle determined the output voltage of our Boost Converter. The more time the gate spent in the "closed" position, the more voltage was built up inside the Boost Converter. The zener diodes (see *Figure 4.3.3 Final Boost Converter Design Schematic*) created a cutoff voltage of 25V, given two diodes in series, having breakdown voltages of V_Z = 10V, 15V. Therefore, the duty cycle needed to create an output voltage greater than or equal to 25V. Equation 2

$$V_{OUT} = V_{IN}/(1 - \text{Duty Cycle}) \qquad (2)$$

relates the input voltage to the output voltage of a Boost Converter. Given our V_{IN} = 8.32 V and our desired $V_{OUT} \geq 25V$, we calculated that the duty cycle needed to be greater than ~66.7%.

From here we used an online 555 timer calculator which gave us the correct resistance and capacitance to reach our specifications. The resulting components were: R_1 = 10 kΩ, R_2 = 4.7 kΩ, and C = 0.001 μF. By researching the pinouts online and discussing with our very helpful TA's, we connected the pinouts of our 555 timer purchased at the EE Store. Figure 3.2.1 below shows the final design schematic for our 555 Timer.

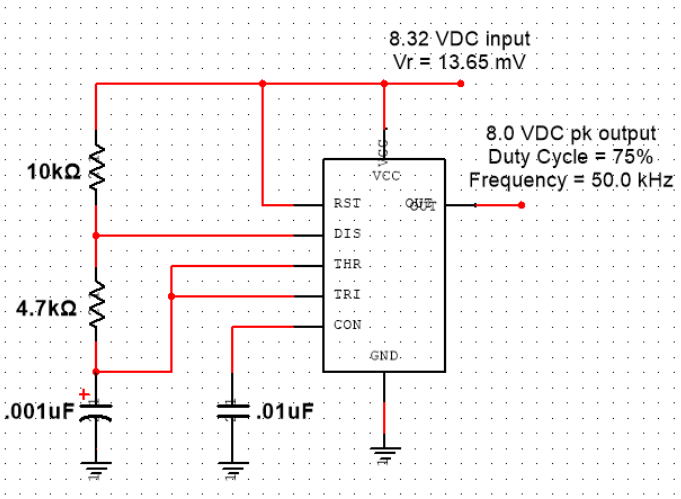

Figure 3.2.1. 555 Timer Schematic

The input of the timer is the VDC value of our bridge rectifier, about 8.32 VDC. This input is the VCC power for the timer. The output of the timer, including its duty cycle, frequency, and voltage, are determined by the components described above which are connected to its pinouts. The voltage outputted by the clock needed to be greater than the "turn on" voltage of the MOSFET in order to turn on the switch in the Boost Converter. The built-in "turn on" voltage of the MOSFET is roughly 0.8V. When we connected the pinouts, components, and sources, we found our output voltage to be about 8 VDC which allows the gate to turn on, as required. See the figures of our clock waveform below.

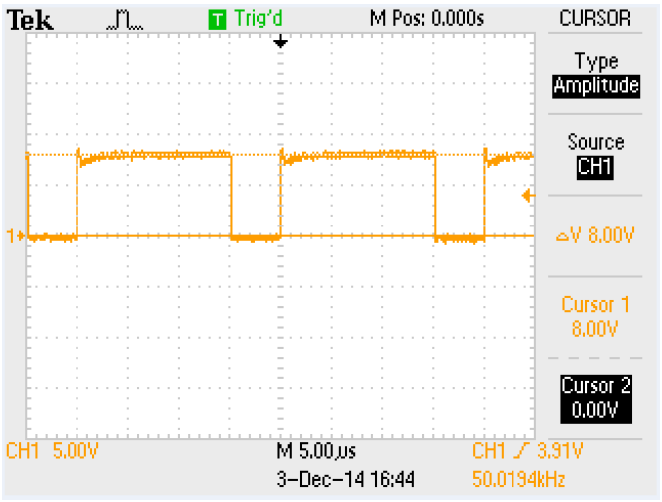

Figure 3.2.2. 555 Timer Output Waveform

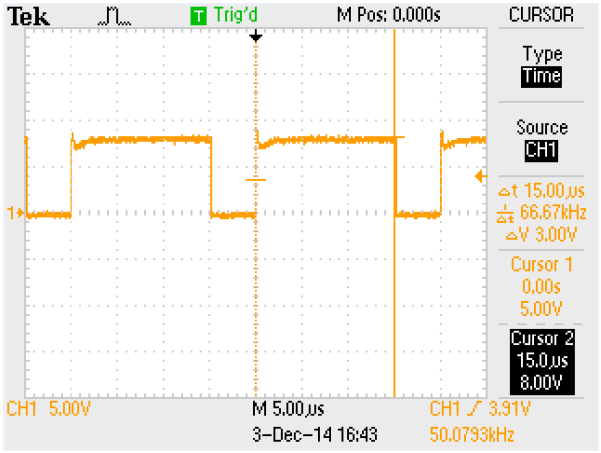

Figure 3.2.3 555 Timer On Time, Δt = 15.0 µs

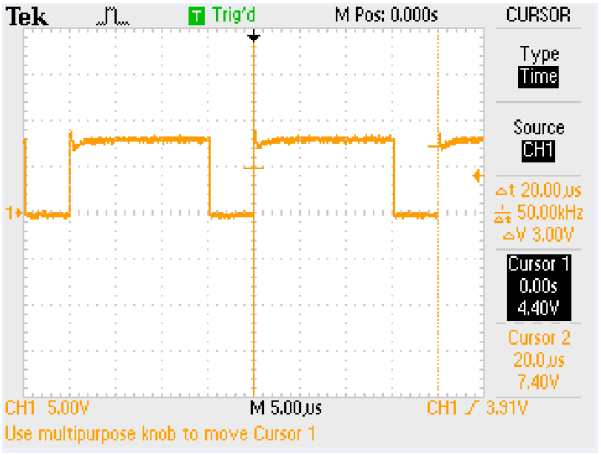

Figure 3.2.4. 555 Timer Period = 20 µs

The amount of time the clock held 8 VDC was 15.0 µs while the total period of the oscillation was 20µs. Therefore, our duty cycle came out to be:

$$(15.0\ \mu s/20\ \mu s) \times 100 = 75\% > 66.7\%$$

as required. The clock frequency, given by the oscilloscope in lab, was 50.0 kHz which meets the requirements given in the assignment, 10 kHz < f < 100 kHz.

Once we finalized the 555 Timer, we moved on to designing and constructing our Boost Converter.

3.3 The Boost Converter

The function of the boost converter is to increase the DC voltage coming from the Rectifier to a large enough voltage that the Voltage Rectifier can vary the output voltage between 10 and 20 volts DC. For our circuit, we decided that we wanted to output approximately 25VDC. To do this, the Boost Converter relies on the concept of conservation of power to try and increase the voltage while decreasing current. To do so, we used a 100 mH inductor connected in series with a 2N7000 MOSFET, M1, with its gate terminal connected the to the *555 Timer* output voltage and a 100kΩ resistor in parallel as shown below in Figure 3.3.1.

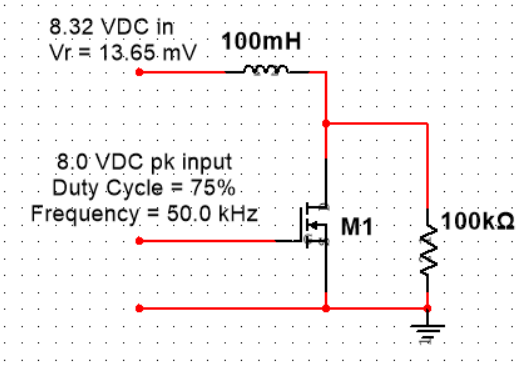

Figure 3.3.1 Initial Inductor Schematic

The purpose of this circuit is to increase the DC voltage coming out of the inductor when M1 was acting as an open switch (*555 clock* input voltage low)and charge itself when M1 was acting like a closed switch (*555 clock* input voltage high). The resistor is there to prevent the inductor from damaging M1 when it is acting as an open switch.

In order to output the larger voltage consistently, we needed to hold the voltage output from the inductor while it charged and M1 acted as a short-circuit. To do so, we added a 33µF capacitor to hold the output voltage from the inductor and a fly-catch diode, D6, to prevent the capacitor from discharging itself across M1 when it was acting as a short-circuit as shown below in Figure 3.3.2.

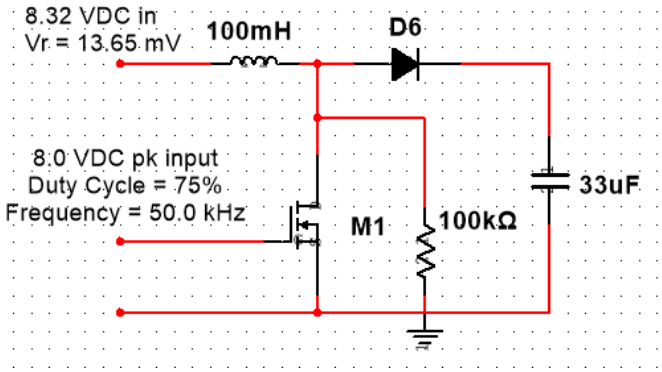

Figure 3.3.2 Boost Converter Schematic

Assuming that the capacitor was large enough to hold its charge despite the load that would be attached and that M1 acts as an ideal switch, we can calculate the output from the boost converter as a function of the voltage drop across the resistor (V_L), charge time (t_{on}), discharge time (t_{off}), and the inductor rating (L). Since we know that an inductor tries to hold the current flow, at equilibrium the current drop during the discharge time ($-\Delta I_{off}$)and the current increase during charge time (ΔI_{on})must be equal. Therefore if:

$$t_{on} = D/f = 15\mu s$$
$$t_{off} = (1 - D)/f = 5\mu s$$
$$V_{L\_Off} = V_i$$
$$V_{L\_On} = V_i - V_{out}$$

We can assume that:

$$\Delta I_{on} = t_{on} * V_{L\_On} / L$$
$$\Delta I_{off} = t_{off} * V_{L\_Off} / L$$
$$\Delta I_{off} + \Delta I_{on} = 0$$
$$(t_{on} * V_{L\_On} / L) + (t_{off} * V_{L\_Off} / L) = 0$$

Therefore by rearranging terms and adding the voltage drop across D6, we get to:

$$V_o = 4V_i - V_{D6} = 33.28 \text{ VDC}$$

However, this output is larger than our intended voltage output for the boost converter. To lower it we used a voltage clipper made of two zener diodes rated 15VDC (1N4744A) and 10VDC (1N5240B) reverse breakdown current respectively connected in series in reverse from the output of the capacitor to ground as shown below.

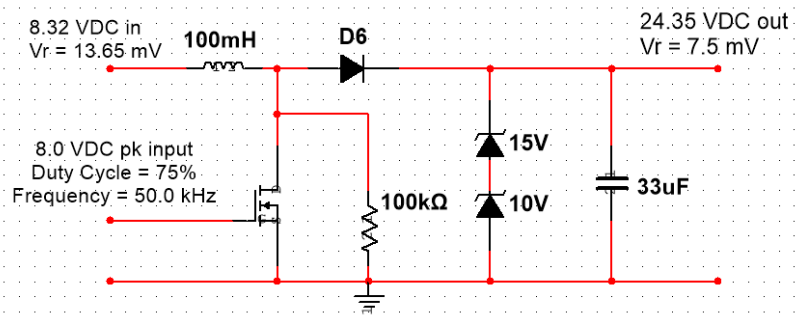

Figure 3.3.3 Final Boost Converter Design Schematic

Overall, the system worked mostly as intended. The capacitor was large enough to keep the ripple voltage smaller than the specified max but was not large enough to supply a constant voltage under load and a small voltage output drop was noticed when the current draw was increased. Otherwise, our boost converter worked as expected with the following values seen in Table 3.3.1.

Boost Converter Output Voltage	24.345 VDC
Boost Converter Output Ripple Voltage	7.510 mVAC

Table 3.3.1 Boost Converter Measurements

The expected output from this circuit was 25 VDC, however due to inaccuracies in the zener diodes the output voltage came out to be 24.35 VDC which was still above our intended final max output voltage of 20 VDC allowing for us to correct it later in the *Voltage Regulator* as described below.

3.4 The Voltage Regulator

The purpose of the Voltage Regulator is to allow the voltage coming out of the Boost Converter to be adjusted anywhere from ~20.0 V to ~10.0 V DC. The voltage coming out of the Boost Converter is typically 24.3 V DC so it had to be decreased to about 20.0 V DC by adding a 4.7 V zener diode (1N4732A) in between the Boost Converter and the voltage divider (as shown in the Figure 3.4.1 below). This brought the maximum voltage down to ~20.1 V. Next, a varying voltage divider was set up using a 10 kΩ potentiometer and a 10 kΩ resistor. The output voltage will be the voltage of the 10 kΩ resistor. This means that any load connected to the power supply will be in parallel with the 10 kΩ resistor. This introduced a problem. Adding a load significantly decreased the equivalent resistance of the bottom part of the voltage divider. This increased the voltage of the potentiometer too much and decreased the output voltage. To fix this we used a 10 V zener diode (1N5240B) to limit the voltage of the potentiometer so the 10 kΩ resistor can always get the voltage it needs. The zener diode we used had a reverse breakdown voltage that

was not close enough to 10.0 V so we added a 1N4007 diode to get the voltage across the potentiometer closer to 10.0 V DC. This effectively controlled the voltage at maximum and minimum voltages with 20 kΩ and 10 kΩ loads, respectively. Figure 3.4.1 below shows the schematic of the Voltage Regulator described above.

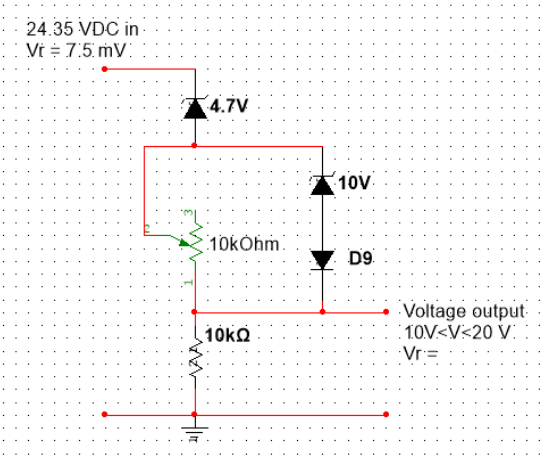

Figure 3.4.1 Final Voltage Regulator Schematic

Table 3.4.1 below shows measurements found (at maximum and minimum voltages) with and without loads.

Set-Up:	DC Output:	Ripple Voltage:
20V - Max. Potentiometer Resistance and No Load	19.996 VDC	7.317 mVAC
20V - Max. Potentiometer Resistance and 20 kΩ Load	19.792 VDC	7.470 mVAC
10V - Min. Potentiometer Resistance and No Load	10.143 VDC	15.265 mVAC
10V - Min. Potentiometer Resistance, 10 kΩ Load	9.701 VDC	5.965 mVAC

Table 3.4.1: Voltage Regulator Measurements

Below is Figure 3.4.1 which shows the ripple voltage at 10V without a load. Again, note the spikes in voltage caused by the inaccuracy of the oscilloscope.

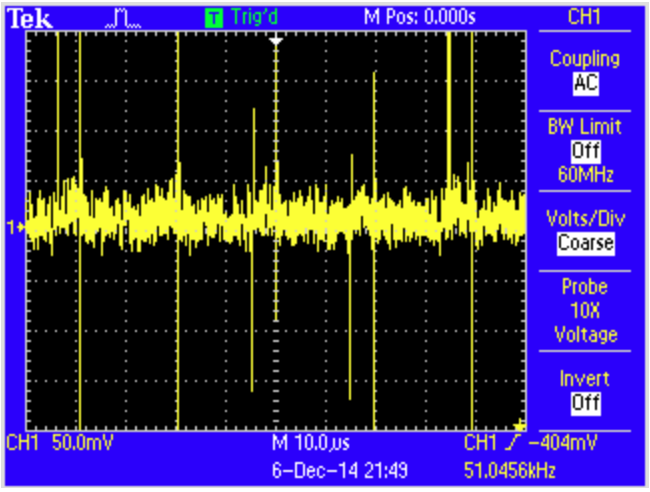

Figure 3.4.1: Waveform of ripple voltage of output voltage at 10V without load (Waveforms for other settings aren't included since they are very similar).

4. Final Multisim Schematic and Simulation

The following measurements were recorded in MultiSim that represent the ideal representation of our constructed circuit. Figure 4.1 below is the final schematic of the entire circuit, inputting 7.5 VAC and outputting between ~10V DC and ~20 VDC.

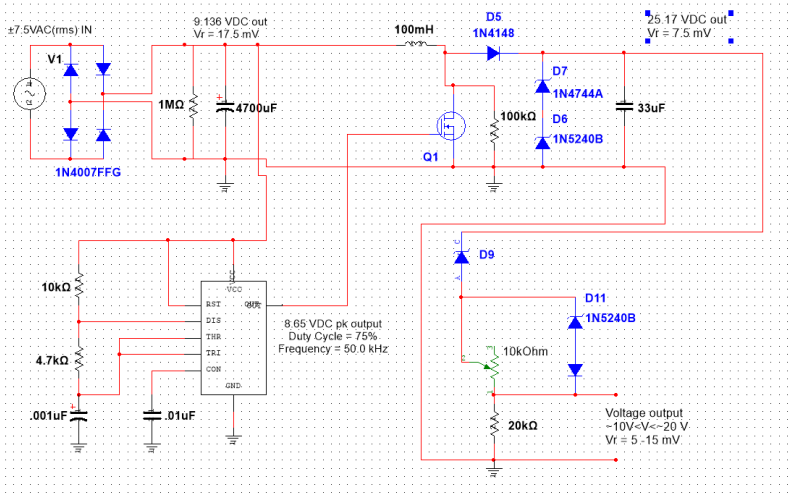

Figure 4.1. The Final Circuit Schematic

First, we simulated the Full-wave Rectifier portion of our design to compare the results found with the real circuit. We found that the simulated circuit produced and output of 9.136VDC which is close to what our real circuit produced, as shown in Figure 4.2. A ripple voltage could not be found because it is nearly negligible, measured to be 17.5mV. The simulated oscilloscope showed a VDC output and the multimeter in simulation measured 0 VAC.

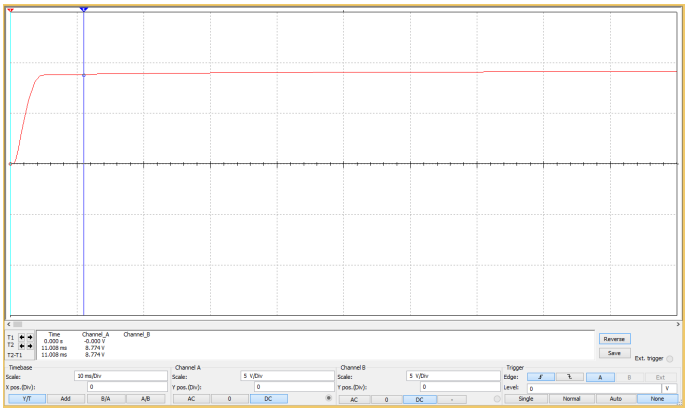

Figure 4.2. Full-Wave Rectifier Simulated Waveform

Next, we simulated the 555 Timer. The output of the timer had a slightly higher voltage peak than our circuit. It measured a peak voltage of 8.65 V. Our circuit may have a lower voltage level because of many reasons. Mainly, the components may not be as ideal as the simulation (e.g. our resistors may not have the ideal resistance or our 555 Timer may not be working under ideal conditions). The simulated output waveform of our 555 Timer is seen below in Figure 4.3.

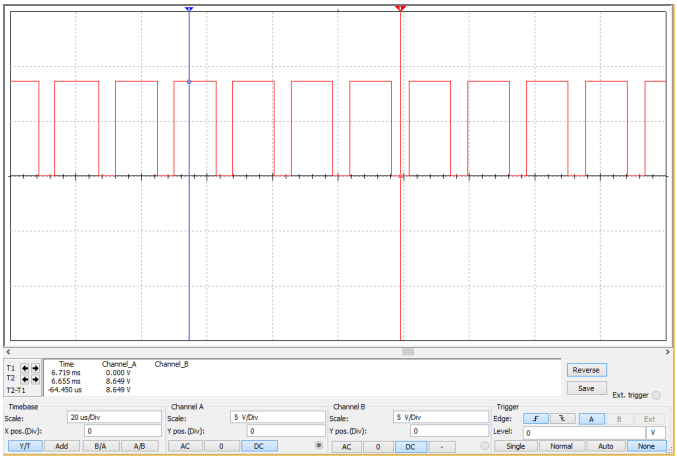

Figure 4.3. 555 Timer Simulated Waveform

We then simulated the output of our Boost Converter. We connected our simulated bridge rectifier and 555 Timer as inputs to the Boost Converter to allow the output waveform to be as close to our real-life circuit as possible. Once our rectifier and clock were simulating correctly, we simulated the Boost Converter and created the waveform below in Figure 4.4.

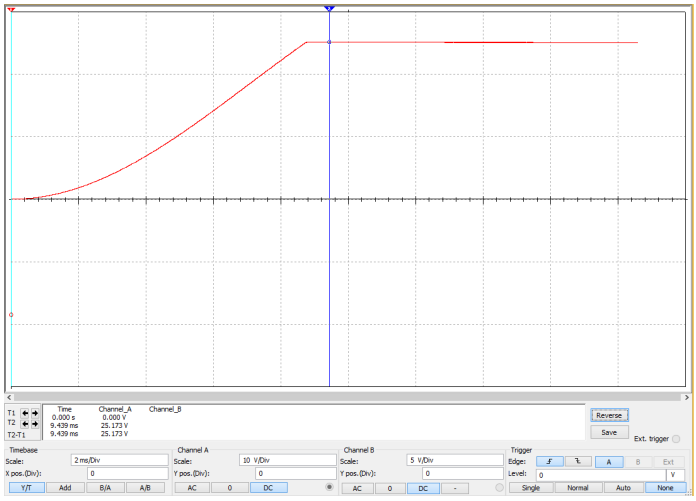

Figure 4.4. Boost Converter Simulated Waveform.

When analyzing Figure 4.4, notice that the output voltage of the Boost Converter is larger than we measured in our circuit. The simulated output voltage is 25.17 V DC whereas our circuit in lab measured at voltage of about 24.3 V DC at this point. This difference can be a result of non-ideal components in real life. While simulation maintains an ideal circumstance, the in-lab values of the zener diode breakdown voltages are not exact, neither are the resistance or capacitance ratings. Also, the ripple voltage measured in lab matches that of the simulation. The ripple voltage in lab was roughly 7.5 mV and the simulation can be seen to have a nearly negligible ripple waveform. This is because the drop in voltage between charging time is close to 0 V, leaving an almost flat, DC output.

Lastly we simulated the four possible outputs of the Voltage Regulator. Namely, a 10 V DC output with/without a 10 kOhm load and a 20 V DC output with/without a 20 kOhm load. In Figure 4.5 we are choosing to only display the waveform of the 20V No Load output for conciseness. The other three waveforms are a nearly flat, DC output with negligible ripple. No matter how far we zoom in we cannot measure an obvious ripple voltage because the max voltage point and the lowest voltage point are too distanced from each other to measure the change in voltage between the points. Also, the multimeter in simulation measures the VAC value to be 0V.

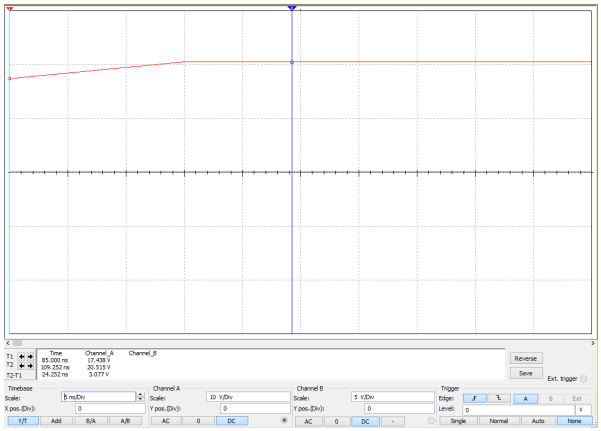

Figure 4.5. 20V/No Load Voltage Regulator Simulated Waveform

Table 4.1. below contains the simulated values of the four possible outputs of the regulator.

Set-Up:	DC Output:	Ripple Voltage:
20V - Max. Potentiometer Resistance and No Load	20.52 V DC	Negligible
20V - Max. Potentiometer Resistance and 20 kΩ Load	20.49 V DC	Negligible
10V - Min. Potentiometer Resistance and No Load	10.3 VDC	Negligible
10V - Min. Potentiometer Resistance, 10 kΩ Load	9.89 VDC	Negligible

Table 4.1 The Voltage Regulator Simulated Outputs

The values in simulation are all larger than what we measured in lab. This can be because the simulation represents an ideal circumstance, whereas our lab components are not their exact ratings.

5. Conclusion

The goal of the final project was to use the knowledge and understanding gained from EE 331 to go through the design process of creating an device that takes in a ±7.5VAC (rms) voltage and produce a variable +10V to +20V output as an electrical engineer would in the industry. We broke down the design into specialized sub-circuits to effectively build this device. The first component of the design needed to convert the AC input voltage into a DC voltage. We chose to design a Full-wave Bridge Rectifier to accomplish this. The Full-Wave rectifier we designed took in a ±7.5VAC (rms) voltage from a transformer and converted it to a ~8.32 VDC voltage.

The next problem encountered was stepping up the voltage from ~8.32 VDC to ~20 VDC. To solve this issue we designed a 555 Timer to produce a clock with a duty cycle of 75% and a frequency of 50.0 kHz to control the next component of the design that increased the voltage, the Boost Converter. The Boost Converter took in the clock signal from the 555 Timer to boost the ~8.32 VDC voltage coming from our Full-wave Bridge Rectifier and produced a DC voltage of ~24.3 V. Finally, we need a method of controlling the output voltage. To do this we designed a Voltage Regulator which took in the ~24.3 V voltage from the Boost Converter and allowed the final output voltage to be controlled from ~10.0 V to ~20.0 V. We found that our design performed very close to the specifications required. However, there are small voltage drops of 0 to 0.5V in the output voltages when loads were applied. This sufficiently met the requirements asked by the lab specifications.