EE 331 Final Project

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1 Project Purpose, Features, and Ratings

The purpose of this project is to design a variable output AC to DC step-up converter/power supply. To achieve this, we'll need a rectifier to convert the AC input to a DC voltage. It will then be necessary to boost the DC voltage to something higher than the maximum desired voltage (20 volts) - we'll do this with a boost topology. The boost topology used will implement a switching transistor, which will be clocked with a square wave oscillator. To produce the square wave, we'll use a 555 timer. Normally, to power the 555 timer we'd just use the DC output from the rectifier, but to able to regulate the output to remain constant even when the load is varied, we'll use a differential amplifier to control the timer. To provide a reference voltage for the differential amplifier, we'll use the 10 volt DC voltage from the rectifier, and a voltage divider with a variable potentiometer. More details for each part, and the design in general, will be available in the sections below.

In addition to meeting the specifications below, the circuit should be optimized in the cost and number of components used. The design encorporates the following specifications:

1.1 External Features and Ratings

- Continuously adjustable output voltage of +10.0 VDC to +20.0 VDC that can deliver from 0.0 to 1.0 mA of current to a load at any voltage in the range above
- Output voltage is adjustable with a single potentiometer
- The final DC output voltage has a ripple of less than 100 mV

1.2 Internal Features and Ratings

- The circuit uses a full-wave bridge rectifier and capacitive filter to produce an unregulated DC voltage of approximately 10 V, with a ripple of less than 1.0 V
- The circuit utilizes a boost topology composed of a transistor-switched inductor, with a catch diode to feed an output capacitor
- The transistor switch in the boost topology is clocked by an on-board oscillator (555 timer) with a frequency in the range of 10 kHz to 100 kHz
- The circuit uses feedback from the DC output to gate the on-board oscillator, which controls the boost topology. Whenever the output voltage falls below the nominal value, the boost circuit switches on to prevent the output voltage from dropping

Please refer to Section 5 for experimental ratings and measurements.

2 Block Diagram

To build the variable output AC to DC boost converter featured in this project, there are six key components: the full bridge rectifier, the voltage divider with adjustable potentiometer, the boost topology, the differential amplifier, the square wave oscillator, and the two large and equal valued resistors. These components, their inputs and outputs, and their relationships to the other components are highlighted in figure 2.1.

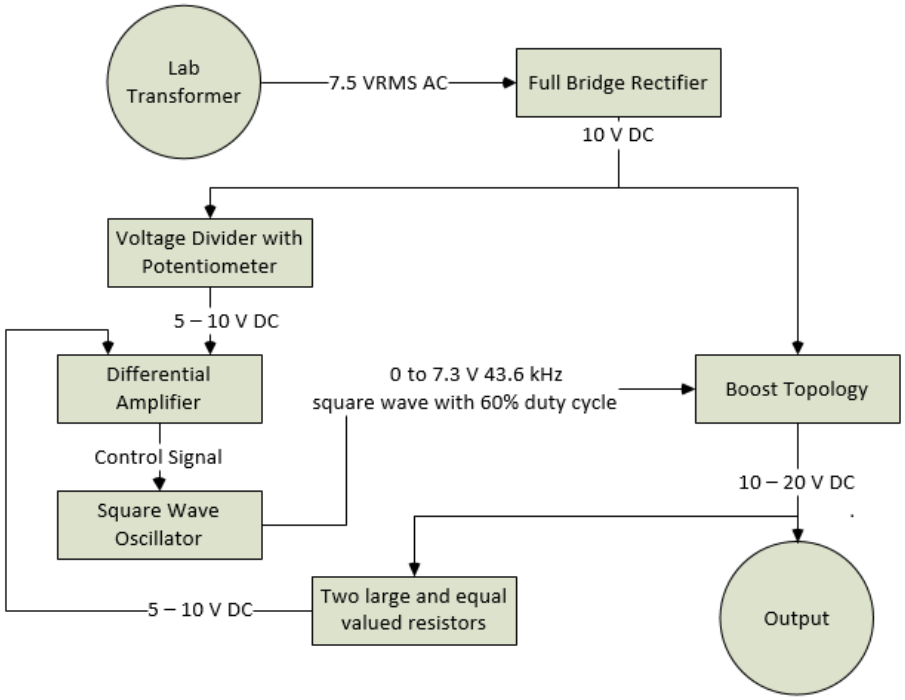


Figure 2.1: High level block diagram

As evident in the block diagram, the full bridge rectifier recieves the 7.5 VRMS AC input from the lab transformer, and outputs a 10 V DC supply. This 10 V supply feeds the voltage divider with potentiometer. The voltage divider, using a potentiometer, is able to output a reference voltage between 5 and 10 volts. The 10 volt output of the full bridge recitfier also feeds into the boost topology which implements a transistor switched inductor.

To actually *boost* the 10 volts to the desired output voltage, a transistor switched inductor is used, clocked by a square wave oscillator. The output voltage of the boost topology is the output of the variable output AC to DC boost converter. The output is fed back into the system - it is first divided in half via two large and equal valued resistors. Since the boost topology is supposed to output 10 to 20 volts, the output of the two large and equal valued resistors is 5 to 10 volts. This is fed into the differential amplifier, and compared to the reference voltage output by the voltage divider.

The differential amplifier is powered by the 10 volt DC source supplied by the full bridge rectifier (not shown). The amplifier sends a control signal to the square wave oscillator - when the output is less than two times the reference voltage, the oscillator is powered on. The oscillator clocks the switching transistor in the boost topology, further boosting the output voltage until it equals two times the reference voltage. When this happens, the amplifier's control signal turns off the oscillator. The oscillator stops clocking the switching transistor in the boost topology, which causes the output to drop. When the output drops below two times the reference voltage, the feedback loop causes the output to be boosted again.

As a result, the differential amplifier is continuously turning the square wave oscillator on and off, to ensure that the final output voltage does not fall below or exceed two times the reference voltage - regardless of the load to the output.

3 Complete Schematic

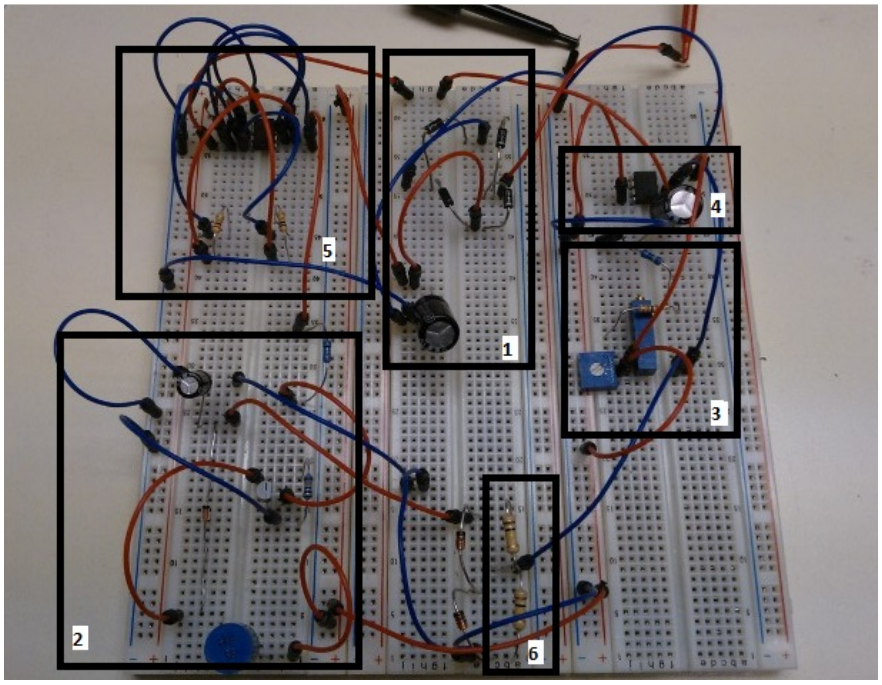


Figure 3.1: Complete circuit implemented on breadboard

The variable output AC to DC boost converter, implemented on breadboards, can be seen in figure 3.1. The 7.5 VRMS AC input is fed into the rectifier (1), which supplies power to the boost topology (2), the voltage divider with potentiometer(3), and the differential amplifier (4). The amplifier sends a control signal to the square wave oscillator (5), which clocks the transistor switch in the boost topology. The output voltage is regulated by a 15 volt and a 5.1 volt zener, in series. The output is divided in half by two large and equal valued resistors (6), which feeds back into the differential amplifier.

Figure 3.2 contains the complete circuitry of the variable output AC to DC boost converter, including component values, and important voltages labelled. These important voltages are

- V_{rect} - the output of the rectifier
- V_{ref} - the reference voltage used by the differential amplifier
- $HalfV_{out}$ - half of the output voltage, also used by the differential amplifier
- BoostControl - controls when the 555 timer is active
- SquareWave - switches the transistor in the boost topology, allowing the voltage to be boosted
- V_{out} - output of the design

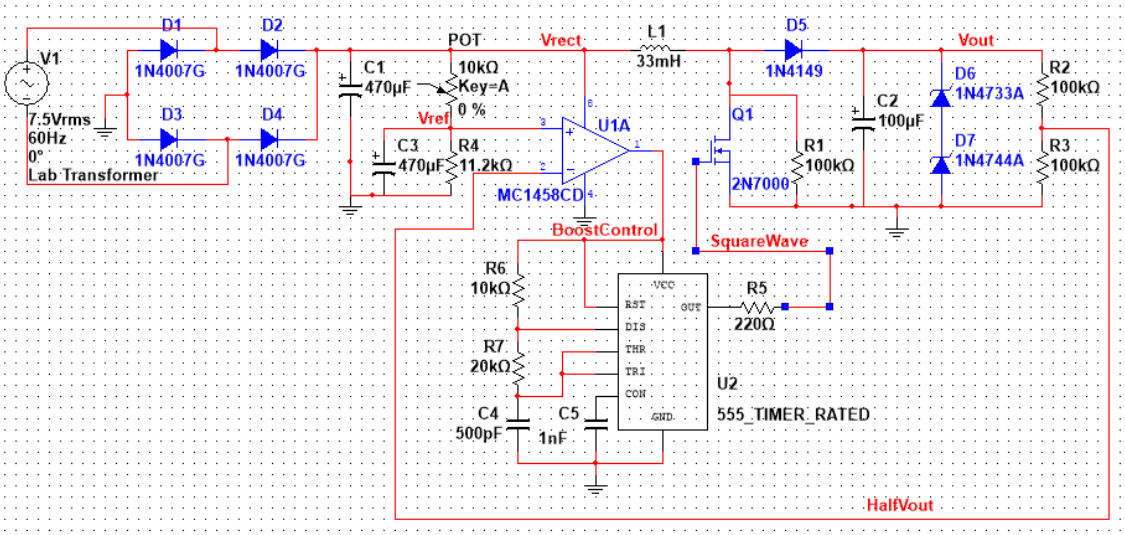


Figure 3.2: Schematic of complete circuit

3.1 Capacitor Values

Most of the capacitors were just used to smooth voltages that tend to vary. C_1 is at the output of the rectifier, to reduce ripple in the 10 volt source, C_2 is used to reduce ripple at the output of the boost topology, and C_3 is used to to reduce the ripple of the reference voltage to help stabalize the behavior of the differential amplifier. These capacitors only needed to be "big enough" to stabilize the output, yet not so big that it took an unreasonable amount of time to vary the output voltage. By testing different capacitor values, we determined that the values in figure 3.2 were good enough.

Capacitors C_4 and C_5 are used to control the square wave oscillator. The frequency and duty cycle of the 555 timer is controlled by equations 1. Please note that the subscripts of the resistor and capacitor values are *not* the same as the subscripts in figure 3.2. Subscripts in equation 1 correspond to the subscripts used in figure 3.3. Resistors R_1 and R_2, and capacitors C_A and C_B in figure 3.3 correspond respectively to resistors R_6, and R_7, and capacitors C_4 and C_5 in figure 3.2.

$$\text{Oscillator output frequency: } f = \frac{1.44}{(C_A)(R_1 + 2R_2)}, \text{Oscillator duty cycle: } D = \frac{R_1 + R_2}{R_1 + 2R_2} \qquad (1)$$

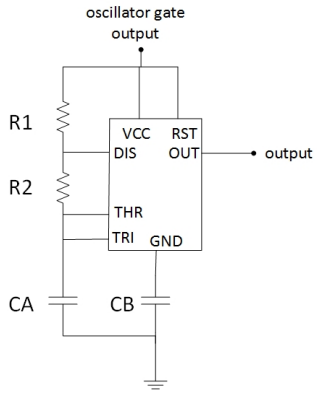


Figure 3.3: 555 oscillator schematic

Since we implemented a feedback loop to control when the oscillator was on, the only restriction on the behavior of the output was that it needed to be able to boost the output voltage to beyond 20 volts. This would allow the control system to regulate the output voltage to the desired value. We determined, with a function generator, that a 45 kHz square wave with a $55 - 60\%$ duty cycle was sufficient. Using the equation $V_{out} = V_{in}\frac{1}{1-D}$, with a duty cycle of 60% and an input voltage of about 10 volts, we could achieve an output voltage of 25 volts.

These two parameters allowed us to determine appropriate resistor and capacitor values via equation 1. Since only the frequency is dependent on C_4, and is also controlled by R_6 and R_7, we picked C_4 to be 500 pF for convenience and planned on using R_6 and R_7 to achieve the behavior we desired. Capacitor C_5 is used to prevent interference, and a typical value of 1 nF is used which is the value we ended up using.

3.2 Resistor Values

The resistor R_1 was arbitrarily picked - it only had to be *large enough* to reduce the transient stage of the boost topology. Resistors R_2 and R_3 were also arbitrarily picked. They only needed to be large to reduce the amount of current drawn through that branch, and equal to each other to divide the output voltage in half. For each of these three resistors, we picked a value of 100 kΩ.

Without resistor R_5, we had trouble integrating the square wave oscillator with the boost topology. With a 10 kΩ load at the output, we found that adding a small resistance to the output of the 555 timer made the output of the boost topology closer to 20 V, as opposed to 17 V. We determined 220 Ω to be good enough to ensure that the boost topology could output a voltage greater than 20 volts. This was *before* the control loop was implemented. We kept the resistor in place after implementing the control loop because it was such a useful resistor before and we didn't want to take it away.

Resistors R_6 and R_7 are used to control the frequency and duty cycle of the 555 timer (see equations 1). Since we desired a frequency near 45 kHz, and a duty cycle near 55%, we used a 10 kΩ and a 20 kΩ, respectively. With these nominal values, we would expect to get a frequency of 48 kHz, and a duty cycle of 60%.

The last resistor, R_4, is used to control the reference voltaged used by the differential amplifier. If the output of the recitifer was an exact 10 volts, then R_4 would need to be 10 kΩ to allow us to divide the 10 volts in half. Unfortunately, the output of the rectifier is not 10 volts. What's

even more unfortunate is that the output of the rectifier varied when we changed lab transformer used. That's because each lab transformer has slightly different peak-to-peak and amplitude values. As a result, we ended up using a potentiometer for R_4 to allow us to callibrate the output of the voltage divider for each lab transformer we used - in figure 3.1 the resistor R_4 is implemented with a rectangular potentiometer in series with some smaller resistors. Please note that this potentiometer is only used to calibrate the device, and *not* used to vary the output between 10 and 20 volts. That behavior is achieved with the square potentiometer labelled POT in figure 3.2. The value of R_4 depicted in figure 3.2 is 11.2 kΩ, which is the value we needed to achieve the desired behavior when using the lab transformer we used during the lab demo. In an actual application, we would have more constant behavior from the transformers, and could use a single resistor for R_4.

3.3 Inductor Value

We originally used a 100 mH inductor, since that's what we used in the previous lab. As described in a prevous section, a duty cycle of 60% would produce an output of 25 volts. However, with a load, this output was less than 20 volts due to a larger amount of current drawn. We decided that instead of changing the duty cycle, we would change the amount of current in the system. When considering the current through the inductor as a function of time, when the transistor switch is closed, the slope is approximately $\frac{V_{in}D}{L}$. So to increase the maximum amount of current drawn, we decreased the inductor value to 33 mH. This produced the desired behavior. However, this was *before* the regulating feedback loop. With the regulating feedback loop, we were able to achieve the desired output with the 100 mH inductor. Similar to resistor R_5, we kept the 33 mH inductor because it was so useful before, and we didn't want to take it away.

3.4 Diode selection

For the rectifier, we ended up using four 4007 diodes since they worked well in a previous lab, and we had no reason to change them. Similarly, diode D_5 was the same diode used in the previous lab - a 1N4148 diode (this is different from figure 3.2 because MultiSim didn't have the right diode...). The zener diodes were picked to regulate the output to less than 20 volts. Unfortunately, we only had a 15 volt, and a 5.1 volt zener. We could have purchased two 10 volt zeners, but we felt that 20.1 volts was good enough, and did not justify buying two components. Essentially, these diodes were selected for convenience - specifically for their low cost, and availability.

4 Impact of the Engineering Solution

4.1 Environmental and Economic Impacts

4.1.1 AC versus DC transmission

The availability of a AC to DC converter allows for the transmission of AC power, as opposed to DC power. AC power is very easy to step up and step down, via transformers, where as changing DC power is relatively more difficult do to in a sustainable way. Due to Joule's law, and power properties it is true that

(1) doubling the voltage and halving the current transmits the same amount of power

(2) the capacity of a wire is proportionate to the square of the current, regardless of voltage

The equations above mean that doubling the voltage, and halving the current, would allow for the transmission of the same amount of power over four times the distance (i.e., less power dissipation). As a result, high voltages are extremely desireable. DC power can not be transmitted at a high voltage because it is very difficult to change the voltage at the consumption end of the line. AC power, on the other hand, can be easily stepped up and down. As a result, it is very easy to step the voltage to a very large value for transmission, and then step it back down to during consumption.

Transmission of AC power is much more efficient, but most devices need a DC supply. AC to DC converter technology makes it possible to transmit AC power, because it can easily be converted to DC for consumption. The invention of an AC to DC converter could possibly reduce the number of power supply stations and the consumption of natural resources, which helps to improve our environmental footprint. This reduction in power supply stations is twofold: since transmission distances have increased, we don't need as many stations to cover larger areas; in addition, since transformers can be used to vary the AC voltage, we don't need special stations for different AC voltages - one source is good enough.

4.1.2 External Converter versus Internal Converter

The AC to DC converter is designed to be separated from the electronics it is powering. For example, laptop chargers are built so that the AC to DC converter is either on the wall socket, or in the middle of the charger, i.e., away from sensitive electronics. This removes heat and noise from the sensitive electronics, which increases their life-expectancy and reduces the amount of electronic equipment replacement. As a result, we've successfully reduced the need to buy new equipment (an economic impact), and reduced the need to consume more materials to build new equipment (an environmental impact). Also, by separating the converter from the other electronics, it makes it possible to replace *just* the converter, as opposed to the entire device - another economic impact.

4.1.3 Variable Output versus Constant Output, and Long Term Impacts

Designing a device capable of a variable DC output reduces the need to purchase multiple converters to produce different output voltages. Instead, one converter can be adjusted and reused with different devices that require different input voltages. By replacing multiple fixed-output converters with a single variable device, consumers and businesses can purchase less and reap economic benefits. In addition to the economic impact, the number of devices that needs to be produced decreases, so the amount of resources used for the purpose of voltage conversion also decreases.

With a variable AC to DC converter, plugs and sockets would ideally be standardized to allow for the optimization of one, or a few, universal converters, as opposed to a different converter for each device. This will greatly reduce the consumption of materials, and drastically impact the electronics industry since each company will be very dissuaded to design their own unique converter like they do today.

4.2 Design Costs and Trade-Offs

4.2.1 Full Bridge Rectifier

The first component of the variable output AC to DC boost converter is the rectifier. Available to us were a half wave rectifier, a full wave rectifer, and a full wave bridge rectifier. We immediately ruled out the full wave rectifier because we didn't have access to a center tapped transformer, and

even if we did, we wouldn't want to use it due to size constraints. This left us with a choice between a half wave rectifier, and a full wave bridge rectifier. For only two more diodes, we were able to reap a significant improvement in output ripple voltage. However, since the voltage was dropping across two diodes at a time, the output DC voltage was a little more diminished in the full wave bridge rectifier. Fortunately, this doesn't matter because we have a boost topology that will be able to produce the output behavior we desire, even with a smaller rectified DC voltage. As a result, our design implements a full wave bridge rectifier to convert the AC input from the lab transform to a DC voltage used by the rest of the design.

4.2.2 555 Timer IC

For our design, we decided to utilize a 555 timer IC instead of building our own square wave oscillator subcircuit. The IC only costs 40 cents, which is similar, or less than, how much square wave oscillator implementations in the lab handbook cost. Furthermore, the 555 timer has a much better shape than most of the designs in the lab handbook. Lastly, the IC has equations (see equation 1) which allow us to easily change the output frequency and duty cycle to our desired output. While our circuit with a the CMOS square wave oscillator would probably produce similar end behavior, we decided to just use the 555 timer IC for the reduction in size, and the better looking square wave.

4.2.3 Capacitor Values

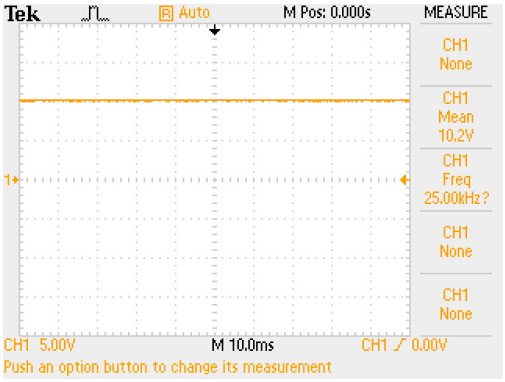
This design, while recieving an AC input, has several DC voltages. Unfortunately, because the DC voltages are derived from an AC input, they contain an undesirable ripple. To decrease the ripple, we can stick large capacitors in parallel to these output voltages. One trade-off with large capacitor values is an increase in delay as well. When varying the final output from the 20 V value to a lower value, if the capacitors are too large, it takes an uncomfortable amount of time for the capacitors to discharge, and as a result, it takes an uncomfortable amount of time to transition between different final output voltages. We had to weigh reducing our ripple voltages against this delay in final output voltage. We decided that, due to the intent of this design, that it was more important to reduce ripple voltages. If the user wanted to change the output voltage, it wouldn't be that inconvenient to wait a few seconds for the voltage to transition; it would be extremely inconvenient if there was a large ripple voltage that disrupted the load device. As a result, we picked large capacitor values to reduce our ripple voltage to well below the project specification. This causes a slight delay of a few seconds between a 20 V and 10 V final output, but we think that that isn't too unreasonable.

5 Test Results

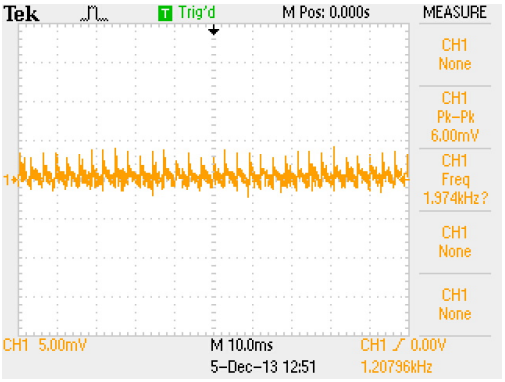
The following sections present our test results, with waveforms as evidence of proper function. A summary of the results are given in Table 5.1, in Section 5.4.

5.1 DC Output and Ripple Voltage

Figure 5.1 shows the DC output voltage and ripple voltage at a 10 V setting, with no load on the circuit. As shown in the figure, the DC output is 10.2 V, while the ripple is 6.00 mV.

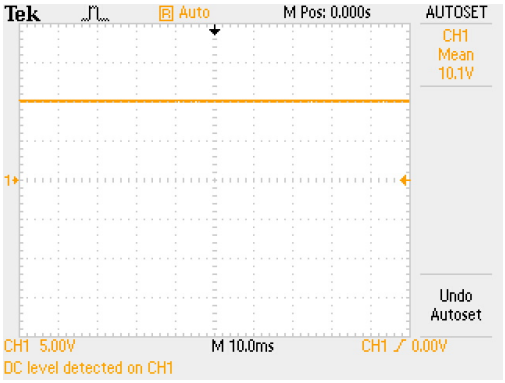


(a) Final DC output

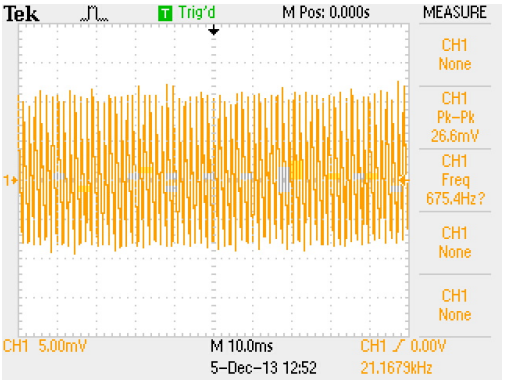


(b) Ripple voltage

Figure 5.1: 10 V setting, no load

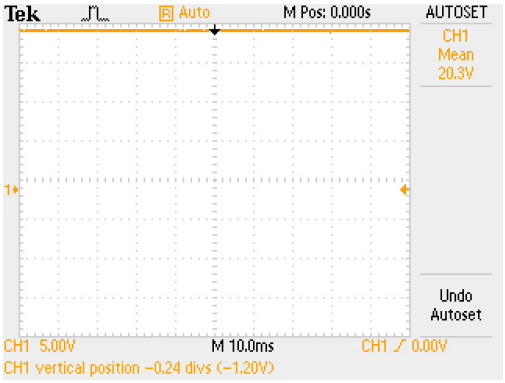


(a) Final DC output

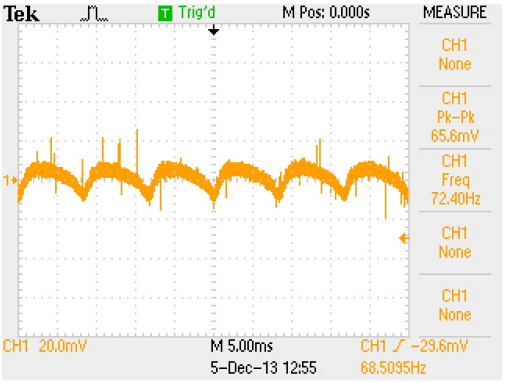


(b) Ripple voltage

Figure 5.2: 10 V setting, 10kΩ load

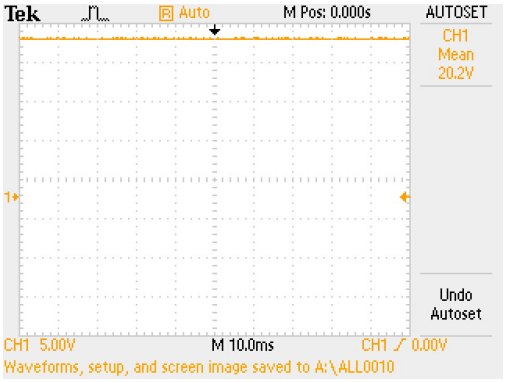


(a) Final DC output

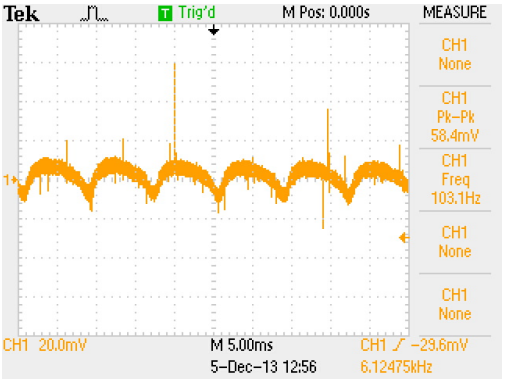


(b) Ripple voltage

Figure 5.3: 20 V setting, no load



(a) Output voltage (20 V, open circuit)



(b) Ripple voltage

Figure 5.4: 20 V setting, 20kΩ load

Figure 5.2 shows the DC output voltage and ripple voltage at 10 V setting, but with a 10 $k\Omega$ load. The oscilloscope measurements show that the output voltage is 10.1 V, with a ripple of 26.6 mV. Similarly, Figures 5.3 and 5.4 show the DC output and associated ripple voltage for an output voltage setting of 20 V, with no load and a 20 kΩ load.

5.2 Rectifier

Figure 5.5 shows the output from the full-wave bridge rectifier. The oscilloscope "CH1 Mean" measurement shows that the output voltage is 9.02 V, and the peak-to-peak voltage indicates that the ripple voltage is 400 mV.

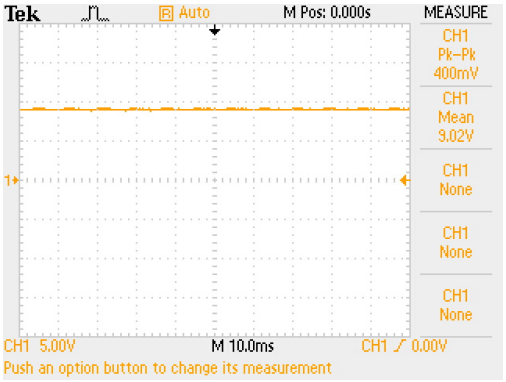


Figure 5.5: Rectifier output

5.3 Oscillator

Figure 5.6 shows the square wave output from the 555 timer/oscillator. The oscilloscope frequency measurement shows that the signal frequency is 43.61 kHz, which is within the acceptable range. The waveform also confirms that the duty cycle is roughly 60%.

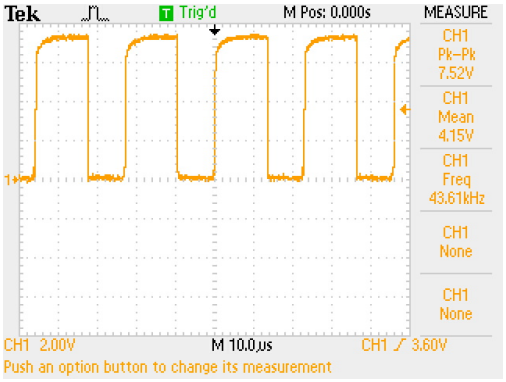


Figure 5.6: 555 Timer/oscillator output

5.4 Summary of Test Results

As evidenced by the waveform diagrams, our circuit meets all of the required specifications (listed in Section 1.1). The test results are summarized in the following table:

Voltage Setting	10 V
Output Voltage open circuit	10.2 V
Ripple Voltage open circuit	6.00 mV
Output Voltage 10 kΩ load	10.1 V
Ripple Voltage 10 kΩ load	26.6 mV
Current through load	1 mA

Voltage Setting	20 V
Output Voltage open circuit	20.3 V
Ripple Voltage open circuit	65.6 mV
Output Voltage 20 kΩ load	20.2 V
Ripple Voltage 20 kΩ load	58.4 mV
Current through load	1 mA

Rectifier Output	9.02 V
Rectifier Ripple	400 mV
Oscillator Frequency	43.61 kHz

Table 5.1: Experimental Results

6 Conclusion

6.1 Final Circuit Behavior

Our design (figure 3.2) satisfied all design requirements in section 1.1. The full wave bridge rectifier produced a DC output close to 10 V, with a 400 mV ripple (less than 1 V); we implemented a boost topology with a transistor-switched inductor, and catch diode; and we utilized a square wave oscillator with a frequency of around 45 kHz. Furthermore, we fed the output of the boost topology through a differential amplifier, with a reference voltage, to control the oscillator. As a result, regardless of the load to our design, the control loop would clock the transistor-switched inductor in the boost topology to bring the output voltage back to the desired value. Our device recieved an input voltage from a 7.5 VRMS AC signal supplied by a lab transformer, and was able to output a continuously adjustable voltage between 10 and 20 V, was varied with a single potentiometer,

and had a final ripple of less than 100 mV. Furthermore, it was able to deliver more than 1 mA of current to a load at any voltage in the 10 to 20 volt range. In other words, our design met every specification, including the extra credit.

On one hand, since we were able to meet all the specifications, we weren't forced to sacrifice one aspect of the desired behavior to achieve another. On the other hand, there are several things we can do to further improve the design beyond what the specifications call for. The first thing we could do is use one 20 V zener at the output, instead of a 15 V and a 5.1 V zener. This cuts down a little on cost, and size! We could also check to see if the resistor R_5 (see figure 3.2), is actually necessary to achieve the desired behavior. This could potentially cut down on cost, and size. The last thing we could do to improve the design is change how the feedback loop is implemented.

6.2 Improving the Feedback Control

As it stands, the feeback control takes the rectified voltage and divides it with a resistor and a potentiometer to produce an output from 5 to 10 volts. This is compared to half of the final output voltage. Since the final output voltage varies from 10 to 20 volts, the differential amplifier compares a 5 to 10 volt line (from the divider), to a 5 to 10 volt line (from the final output. Unfortunately, our rectifier does not produce 10 volts. The rectified DC voltage is also very dependent on the lab transformer used, which means we need to calibrate the divider to actually produce 5 to 10 volts every time we change input sources. That is bad. One solution we could do is divide the final output by four, with one 50 kΩ resistor, and a 150 kΩ resistor. Then we could use a zener diode to produce a constant 5 V DC line, which would not vary when we changed inputs. Then we could use a potentiometer and 10 kΩ resistor to produce a reference votlage of 2.5 to 5 V. This would produce a similar behavior to what we currently have, without the need to calibrate every time the input is changed.