Electrical Engineering Department

California Polytechnic State University

Senior Project Final Report

Cascaded Voltage Clamping and LDO Offline Power Supply

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Abstract

Offline power supplies are necessary for any sort of electronic device that utilizes wall power. For offline power supplies, it is a common practice to use the switching mode method where the high voltage AC input is first rectified and then switched at high frequency to a much lower voltage. This method has been known to be very efficient. Also, it's more efficient than a linear supply method where the AC input is stepped down and then linearly regulated down to a low voltage. Despite the efficiency benefit, the switching method employs a high frequency transformer and inductor. This will make the design relatively costly and bulky (especially at a very low output power). This project will look into a new method of producing a low DC voltage from a high AC input voltage. The method utilizes a switch that prevents the power supply to charge a rectifier capacitor filter all the way up to the peak of the AC input voltage. Rather, the input is clamped at a much lower voltage that is closer to the output voltage such that a low dropout (LDO) regulator could be used; thus, avoiding the use of an inductor while maintaining the high efficiency. The proposed design was tested through LTSpice simulation and results demonstrated the functionality of the design in achieving the desired output voltage. The efficiency of the power supply with the proposed input clamping and LDO method was measured to be above 70% at full load. Construction of a prototype for the proposed design was planned but was not carried out due to the COVID-19 pandemic.

Chapter 1. Introduction

In today's society, electricity is a widely available resource. According to the world-bank data, 89% of the entire world population has access to AC power [1]. Most of this AC power is being used to power daily necessities such as lighting, cooking, storage, computing, etc. Additionally, in the past decade we have been experiencing the increase in the use of DC loads which are mainly coming from consumer electronics such cellphones, tablets, laptops, and others. Another DC device that has recently become more prevalent is the LED lights. With such a high demand for DC power, there is a need to convert the large AC voltages to small DC voltages. This process needs to be done efficiently because of the vast scale of the total energy being converted. On the device level, we should also strive for low cost options to do the conversion because electricity is a necessity to everyday life. This AC to DC conversion can be effectively accomplished through the use of what is known to be offline power supplies. These power supplies are power converter circuits that are able to convert AC voltages (typically those accessible from wall outlets) to DC voltages for the use of household electronics and appliances.

There are two types of offline power supplies: linear and switching modes. The switching mode power supplies, also known as the switched-mode power supplies (SMPS) utilize a conversion technique called power electronics that make them more efficient than their linear counterparts. "A switched-mode power supply is an electronic circuit that converts power using switching devices that are turned on and off at high frequencies, and storage components such as inductors or capacitors to supply power" [2]. As a result, they are used in power supplies these days. Moreover, their physical size per given watts is significantly smaller than that of the linear power supplies, as illustrated in Figure 1-1. However, they can be expensive when considering the number of components needed to construct switched mode topologies. Also, magnetic

components like inductors and capacitors can be both expensive and bulky. Another problem

associated with the SMPS is the electrical noise known as electromagnetic interference (EMI)

noise that they generate [3]. This noise, if not filtered and shielded properly, will affect, and

sometime disrupt, the operation of any neighboring electrical systems. The EMI filter and shield

being used for SMPS will consequently add to their overall cost.

Figure 1-1: *A 400W switching power supply (left) vs. a 90W linear power supply (right) [4].*

Linear power supplies on the other hand work based on dividing the input voltage to

achieve the output voltage. In other words, to obtain a lower output voltage, the difference

between the input voltage and output voltage will have to appear between the input stage and

output state. This may result unfortunately in significant power loss especially when the output

voltage is at a much lower voltage level than the input voltage. A good example would be

powering a 5V USB device from the wall outlet that gives approximately 170V in the U.S.

However, their benefits lie in their simplicity and therefore low-cost. They are also "quiet" since

no noise is practically generated from these power supplies [5].

Knowing that both types have their advantages and disadvantages, their use will therefore be determined by what objectives the system or the designer would like to accomplish by the power supply. An electric car or airplane will most likely use the switching type since the system needs to be light. Communication systems will utilize the linear type since a very low noise level is important in such a system. However, for some systems the choice may not be so obvious. An example of this would be the power supply for the LED light bulbs.

Chapter 2. Background

Offline power supplies are essential for everyday life because they are necessary for any sort of electronic device that utilizes wall power. Due to the importance of offline power supplies, engineers are constantly looking for ways to improve upon different designs and methods of implementing these power supplies. There are two typical methods of stepping down voltage after it has been rectified from the original AC voltage and those methods include switching regulators and linear voltage regulators [6].

Linear regulators are used solely to step down voltages. One variation of linear regulators is called Low-Drop-Out (LDO) regulators. Essentially, linear regulators operate based on the voltage division concept that continually adjusts using feedback resistors to keep a constant output voltage. This can be seen in Figure 2-1a. A more accurate representation of the base circuit of a linear regulator can be seen in Figure 2-1b. Figure 2-1b shows that linear regulators also include an error amplifier and a solid-state device to keep a constant and regulated output voltage. Linear regulators are more efficient than switching regulators when the difference between input voltage and output voltage is small. Also, they have a fast-transient response in comparison to switching regulators since their output is always electrically connected to the input.

Switching regulators are voltage regulators that can step up or down voltage. Switching regulators rely on the duty cycle of the switches to regulate output voltage. The output voltage of a switching regulator is a function of duty cycle. There are two main modes of operation in which switching converters operate. The first state is when the top switch in Figure 2-2 is conducting and the bottom switch is off. The other state is the reverse. The circuit in Figure 2-2 is a buck converter which is just one type of switching regulator. However, all switching

regulators consist of three main power components: a switch, diode (could be replaced with another switch as seen in Figure 2-2), and an inductor. Depending on the orientation of these components you can step up or step-down voltage. Switching regulators have a high efficiency especially in high power applications [7].
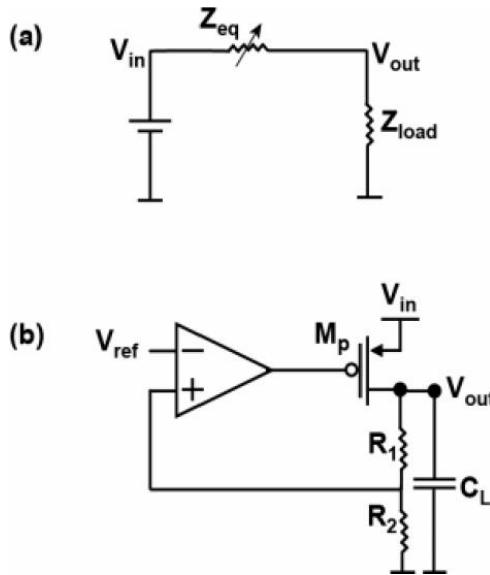

Figure 2-1: *Linear Regulator Topologies [7]. (a) Basic LDO regulator with variable resistor (b) Practical implementation LDO regulator*
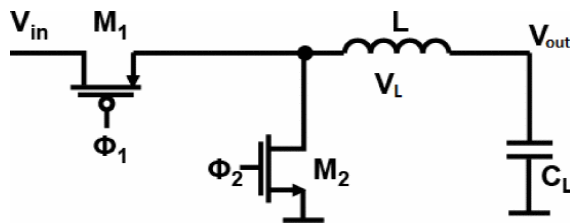

Figure 2-2: *Switched Inductor Buck Converter [7]*

There are advantages and disadvantages with both of these options. In the high-power applications, a switching regulator would be more ideal than a linear regulator because of its higher efficiency. Typically, linear regulators are used in low power applications. However, they can be used in applications in which the difference between input to output voltage is large if efficiency is not a considerable factor. One disadvantage of switching regulators is that it requires the use of an inductor. The inclusion of an inductor would increase the number of components, make the circuit design more complex, require a larger form factor, and make the overall design more costly [7]. Table 2-1 further outlines the benefits of both linear regulators and switching regulators [8].

Table 2-1: *Benefits of Linear and Switching Regulators [8]*

	Linear Regulator	**Switching Regulator**
Design Flexibility	Buck	Buck, Boost, Buck-Boost
Efficiency	Normally low to medium-high for low difference between V_{IN}-V_{OUT}	High
Complexity	Low	Medium to high
Size	Small to medium, larger at high power	Smaller at similar higher power (depending on the switching frequency)
Total Cost	Low	Medium to high
Ripple/Noise/EMI	Low	Medium to high
V_{IN} Range	Narrow (depending on power dissipation)	Wide

Another considerable downside to switching regulators is that they generate a lot of switching noise in comparison to their linear regulator counterpart. There are different options that can be implemented to alleviate this switching noise such as filters and multi-phase

topologies. However, for applications that require a "quiet" DC source such as communication systems, digital electronics, or RF electronics it might be better to use linear regulators despite the fact that their overall efficiency could potentially be less than that of a switching regulator [9]. One other thing to consider is the actual cost difference between these two types of regulators must be considered. In Sanket Gupta's article "How to Select a Voltage Regulator", he briefly gives an example of the kind of cost disparity that can exist between switching regulators and linear regulators. In this example he shows that the LD1117 (a linear regulator) is approximately $0.50, while the LMR12010 is approximately $7 [10]. While this is just one example of two different chips, it gives an idea of the kind of cost disparity there is between linear and switching regulators.

These concerns bring us to another idea for this project to design a circuit that would directly utilize a linear regulator instead of a switching regulator without the use of a step-up transformer in an offline power supply. To do this, the voltage from the wall would first need to be clipped to a voltage of 5V for the linear regulator to operate at. At this clipped voltage, a linear regulator would be able to step down the voltage to 3.3V. The use of a linear regulator topology will be easier to implement and more cost effective over a switching regulator topology. This project will be to provide a proof of concept to see if the solution is actually viable both technically and economically.
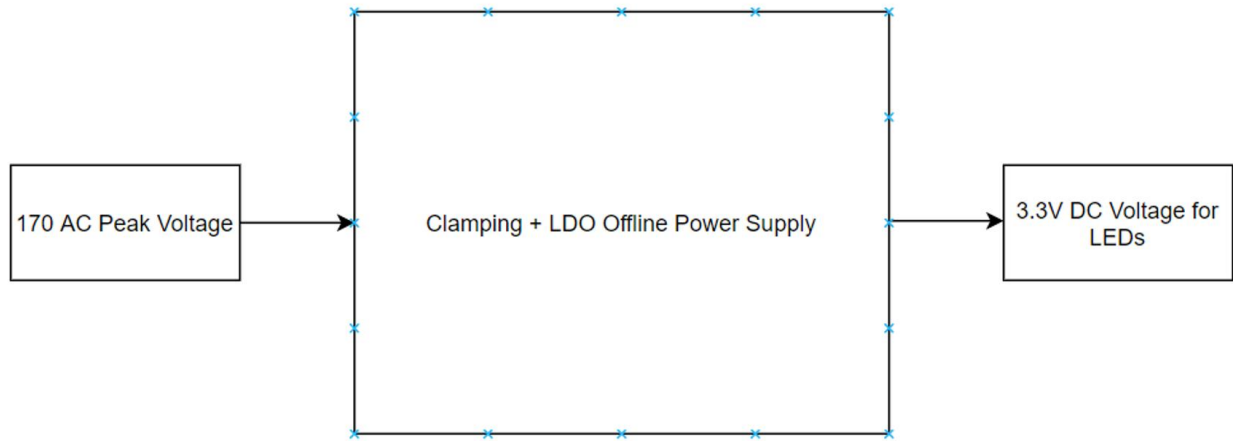
Chapter 3. Design Requirements

Figure 3-1: *Level 0 Block Diagram*

The Level 0 block diagram is shown in Figure 3-1. This diagram ultimately just shows the overall input and desired output of our system. The power supply will take in $170V_{AC}$ or equivalently 120Vrms (wall voltage) and then convert it to $3.3V_{DC}$ for use by a DC load such as LED light.

Figure 3-2: *Level 1 Block Diagram*
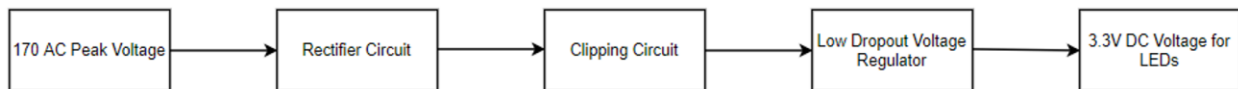
The Level 1 block diagram is shown in Figure 3-2. This diagram goes into more details about the processes of converting the wall voltage to the desired voltage of $3.3V_{DC}$. Essentially, the design for this project will take in the 170 V_{AC} from the wall and rectify that voltage through a full bridge diode rectifier circuit. From there, a clipping circuit will clamp the rectified AC

voltage to about 5V peal. Following this, the resulting clamped DC voltage will be stepped down to the desired $3.3V_{DC}$ using a low-dropout voltage regulator to power LEDs.

Technical Design Requirements:

One of our major requirements for this design is that it should be competitively priced in comparison to the traditional switching power supplies. Our design will not include a switching DC-DC converter circuit controller along with its associated inductor. This approach is done so that ultimately the cost of our product will be significantly reduced. Our design will include several circuits such as a full wave rectifier circuit, a window comparator/clipping circuit, an LDO, and passive components. These devices in addition to the production cost, (the cost to fabricate the PCB) will be priced to be less than $10 per prototype unit. Eventually, when mass produced the cost will even be much lower, in the order of less than $1. This is much cheaper than the typical cost of a switching power supply used for the same purpose. Also, because of the limited amount of components needed to create our product we can create a really compact circuit. The desired form factor of this circuit will be 40mm x 40mm. This form factor was determined by the size of the components that are rated for $170V_{Peak}$. Since the product is expected to have very few components it should be easy to troubleshoot and therefore very reliable. This design will need to clip the input ($170V_{Peak}$) to ~ 4V-5V in order for the linear regulator to step down the voltage to the final output of $3.3V_{DC}$ at 10mA for the LEDs. The projected efficiency for this design should be around larger than 70% at full load.

Electrical Specifications:

Tables 3-1 through 3-2 summarize the electrical design requirements for the major components of this project along with their relevant justification.

Table 3-1: *Level 1 Full Wave Bridge Rectifier*

Module	Full Wave Bridge Rectifier
Input	$120V_{RMS}$ sinusoid from wall outlet
Output	Unfiltered Full Wave Rectified $120V_{RMS}$ sinusoid
Design Requirements	• Vin = $120V_{RMS}$ • Vout = Full Wave Rectified $120V_{RMS}$ The input voltage will be $120V_{RMS}$ from the wall outlet. The full wave bridge rectifier should be able to handle up to $170V_{Peak}$, and output the correct full wave rectified sinusoid.
Functionality	This circuit will be used to convert all of the negative voltage to a positive value to be used by the clipping circuit and linear regulator.

Table 3-2: *Level 1 Clipping Circuit*

Module	Clipping Circuit
Input	Full Wave Rectified $120V_{RMS}$ sinusoid
Output	Capacitor Voltage windowed between 4V - 5V
Design Requirements	- Vin = Full Wave Rectified $120V_{RMS}$ - Vout = Capacitor Voltage windowed between 4V - 5V The input voltage will be the full wave rectified $120V_{RMS}$ from the bridge rectifier. The input voltage will be compared within a voltage window comparator. The comparator is set to 4V - 5V so that it will determine when to turn on and off both switches. The input switch needs to be rated at 170V due to the peak voltage from the bridge rectifier.
Functionality	When the voltage is compared above 5V, the comparator will send an active low to the switch at the input to turn off the switch, while the active low signal will be inverted and turn the switch to the output on. The turning on and off the switches will determine the necessary output voltage from the clipping circuit to be within 4V to 5V.

Table 3-3: *Level 1 Linear Regulator*

Module	Linear Regulator
Input	Capacitor Voltage windowed between 4V - 5V
Output	3.3V (DC) at 10mA
Design Requirements	- Vin = Windowed voltage between 4V - 5V - Vout = 3.3V (DC) at 10mA
Functionality	The linear regulator will regulate the windowed voltage of 4V - 5V to a DC voltage of 3.3V with a load current of 10mA.

Chapter 4. Design

The LDO + Clamping circuit is designed to be a low-cost and compact way of converting AC voltage to DC voltage. To demonstrate this, the circuit includes a small LED that will draw 10mA. The minimalistic design of the clipping circuit makes this design unique and ultimately eliminates the need for an isolated topology (no transformer). It also converts the rectified AC voltage to an acceptable voltage that can be used by the LDO. The clipping circuit does this by only allowing an average voltage of 5V to be at the input into the LDO. The Level 2 block diagram of Figure 4-1 shows a more in depth look at the different stages of this circuit.

In this design, there are two stages for this circuit to work: the power and control stages. The power stage is the section of this circuit that handles the incoming AC voltage and power. The switch functions to limit the voltage on the input of the linear regulator. The capacitor after the switch is needed to hold a constant voltage when the switch is switching. The control stage consists of a voltage divider, comparator, and a high side driver. The voltage divider consists of a resistor and capacitor to create a reference voltage to power the high side driver and comparator. It also acts as a reference for the comparator. If the input voltage is less than the reference voltage of 11V then the comparator will output 0V; otherwise, it will output a pulse of 11V. The comparator then sends this pulse to the high side driver. The high side driver amplifies the signal out of the comparator so that it has enough current and voltage to drive the gate of the MOSFET.
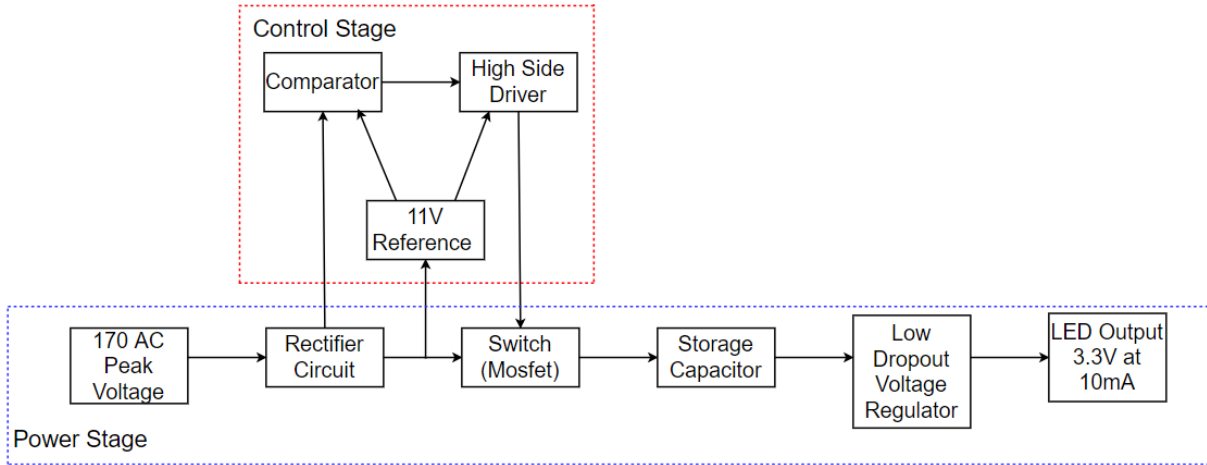
Figure 4-1: *Level 2 Block Diagram*

Due to the nature of this circuit, either full wave-rectifier or half-wave rectifier may be utilized at the input of the circuit. To determine what components were needed for each design with the different rectifier, the voltage, current, power dissipation, and rectified waveform were considered for each component. The following calculations show the minimum input capacitor needed for both circuits and the efficiency of the LDO:

Full Wave

Capacitor equation is first used:

$$I_{In} = C_1 \frac{dV_{C1}}{dt} = C_1 \frac{\Delta V_{C1}}{\Delta t}$$

where ΔV_{C1} is the desired input ripple voltage to the LDO, and Δt is the period of the rectified waveform. The capacitance value can now be computed:

$$C_1 = I_{In} \frac{\Delta t}{\Delta V_{C1}} = (10mA) * \frac{\frac{1}{2*60Hz}}{6V - 4V} = 41.67 \mu F$$

Half Wave

Capacitor equation is again first used, and from which the capacitance value can be obtained:

$$I_{In} = C_1 \frac{dV_{C1}}{dt} = C_1 \frac{\Delta V_{C1}}{\Delta t}$$

$$C_1 = I_{In} \frac{\Delta t}{\Delta V_{C1}} = (10mA) * \frac{\frac{1}{60Hz}}{6V - 4V} = 83.33\mu F$$

Efficiency of the LDO

$$P_{in} = V_{In}I_{In} = (5V) * (10mA) = 50mW$$
$$P_{Out} = V_{Out}I_{Out} = (3.3V) * (10mA) = 33mW$$
$$\eta = \frac{P_{Out}}{P_{In}} = \frac{33mW}{50mW} = 66\%$$

The efficiency of LDO would essentially be the same in both circuits. However, utilizing

LTSpice the efficiency of a full wave bridge rectifier was found to be 81.2% compared to 40.6%

for a half wave bridge rectifier. Figures 4-2 and 4-3 feature the system design using full bridge
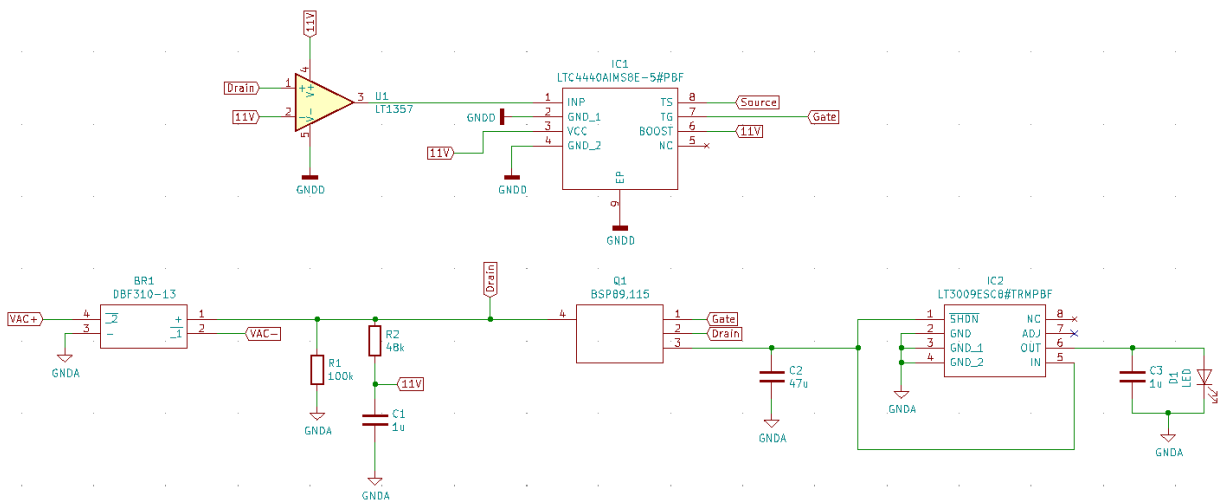
and half bridge circuits.
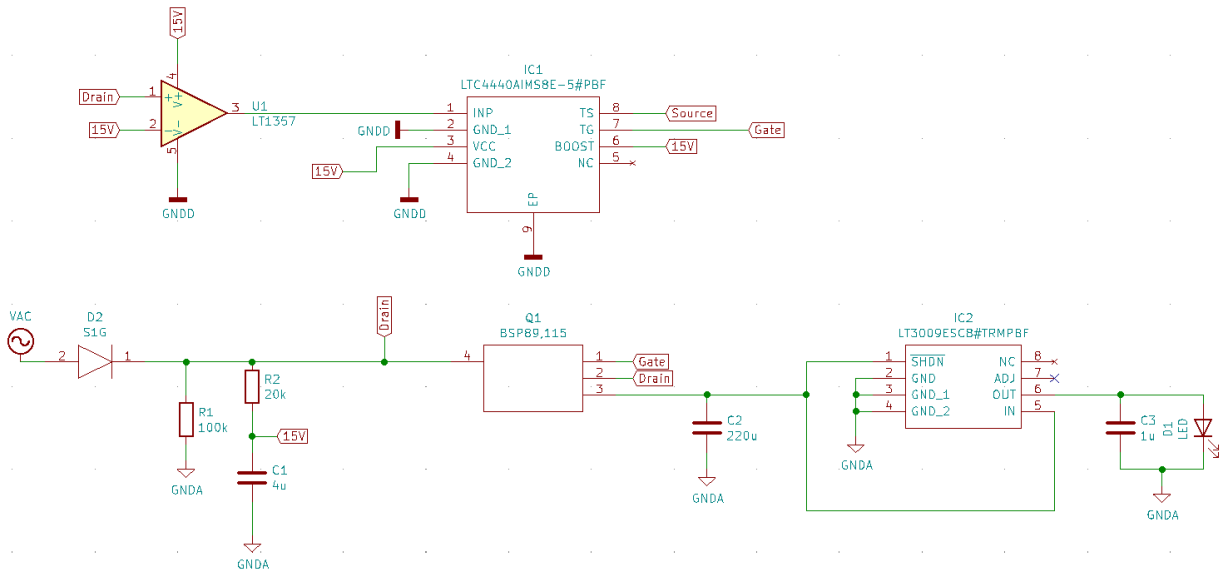
Figure 4-2: *Full Wave Circuit Schematic*

Figure 4-3: *Half Wave Circuit Schematic*

The input to these circuits will be a 120V$_{RMS}$ ±5% sinusoid from a wall outlet.

Considering this high input voltage, any components on the input must be rated to handle at least

$(1.05 \times 120\sqrt{2}) = 178.5V_{Peak}$. Thus, the bridge rectifier for the full bridge circuit and the diode for

the half bridge are rated for larger than 178.5V$_{Peak}$. When the switch is open, a resistor is needed

in parallel with the bridge rectifier to ground for a path for current to flow. Without this resistor,

the switch would disrupt the input voltage and current. Since the input has such a high voltage,

the resistor value needs to be large to minimize power loss across the resistor. A 100kΩ resistor

leads to a power dissipation of 138.09mW. Thus, a minimum power dissipation rating of 200mW

is chosen. The op amp is needed to compare the full wave rectified signal to a 15V reference

voltage. The op amp needs to be rated for 170V to the negative terminal and at least a 15V peak

to the power rail and positive input terminal. The high side driver needs to be rated for an input

pulse from the comparator up to 15V and a reference voltage from the voltage divider of 15V. Since the reference voltage is connected to the power rail and positive input of the op amp and the VCC pin of the high side driver, a typical resistor voltage divider would dissipate too much power. A resistor and capacitor would be able to act as a voltage divider to create the correct reference voltage. It would also minimize power dissipation. Since the desired reference voltage is 15V, the capacitor would be rated at a minimum of 15V. The best value for the resistor to produce the correct reference voltage with the least amount of power dissipation is 48kΩ. This was found through the aid of LTSpice because the surrounding components made it difficult to find an adequate resistor value. The closest nominal resistor value with the least amount of power dissipation is 47.5kΩ with a power dissipation rating minimum of 250mW. To limit the amount of voltage going into the LDO, the MOSFET would need to be able to handle the peak voltage from the rectifier circuit of 178.5V. To determine what value was necessary to lower the ripple of the input to the LDO, the equation for input capacitance, C2, is first implemented. After observing the input voltage to the LDO in simulation, the capacitance is increased for the best result without being too large and expensive. The chosen value for this capacitor that met the voltage window while not being too large and expensive is 47μF. With the desired input voltage to the LDO to be between 4-6V, the voltage rating of the capacitor at the input to the LDO would need to be at least 6V. After choosing an LDO that meets the requirements specified above, the datasheet shows a necessary 1μF capacitor across the load to reduce to ripple. Due to the low output voltage, the 1μF capacitor chosen from the voltage divider would be more than sufficient for the output capacitor.

The following components shown in Table 4-1 are the Bill of Materials listing the chosen components from the rated specifications above for the full wave circuit.

Table 4-1: *Bill of Materials Utilizing Full-Wave Rectifier*

Count	RefDes	Value	Description	Size	Part Number	Manufacturer	Per Unit Cost $	Total Cost $
1	R2	47.5kΩ	Thick Film Resistors - SMD 0805 47.5Kohms 0.5W 1% AEC-Q200	0805	ERJ-P06F4752V	Panasonic	$0.15	$0.15
1	R1	100kΩ	Resistor, Surface mount, 0603, 1/5W, ± 0.5%	0603	ERJ-PB3D1003V	Panasonic	$0.18	$0.18
1	C2	47uF	Capacitor, Electrolytic, SMD, 6.3V, ± 20%	5.3mm x 5.3mm	UWX0J470MCL 1GB	Nichicon	$0.31	$0.31
2	C1, C3	1uF	Capacitor, Electrolytic, Through Hole, 50V, ± 20%	5mm x 12.5mm	UVK1H010MDD 1TD	Nichicon	$0.27	$0.54
1	D1, D2, D3, D4	-	BRIDGE RECT 1PHASE 1KV 3A DBF	8.5mm x 6.45mm	DBF310-13	Diodes Incorporated	$0.53	$0.53
1	M1	-	MOSFET N-CH 240V 375MA SOT223	6.3mm x 6.7mm	BSP89,115	Nexperia	$0.53	$0.53
1	U1	-	LDO Voltage Regulator, 3uA, Vin = 20V, Vout = 3.3V	2mm x 2mm	LT3009ESC8#T RMPBF	Analog Devices/Linear Technology	$2.49	$2.49
1	U2	-	Gate Driver High & Low Side Driver	3mm x 4.9mm	LTC4440A-5	Analog Devices/Linear Technology	$2.33	$2.33
1	U3	-	IC OPAMP VFB 1 CIRCUIT 8SO	0.189mm x0.228m m	LT1357 CS8#TRPBF	Analog Devices/Linear Technology	$2.45	$2.45
1	P1	-	CORD 18AWG NEMA1-15P - CBL 3.28'	3.28' (1.00m)	223053-01	Qualtek	$1.57	$1.57
1	L1	-	LED RED CLEAR 5MM ROUND T/H	10.10mm x 5mm	CP41B-RFS-CM0P0EE4	Cree Inc.	$0.15	$0.15

Like the full wave rectified components, most of the half wave components would have the same voltage rating. However, since the rectified waveform is 0V for half of the period, a few of the passive component values would need to be adjusted to accommodate for the longer

off time of the rectified waveform. Also, the bridge rectifier in the full wave version would be replaced with a single diode rated at higher than $178.5V_{Peak}$ instead. The reference voltage of approximately 15V stays the same, but to produce that reference voltage, the resistor and capacitor values of the voltage divider were changed. To determine the appropriate values for the resistor and capacitor, the full wave passive component values were adjusted until a similar output to the full wave is observed. The optimal resistor and capacitor values to produce a similar output as the full wave circuit is 20kΩ and 4μF, respectively. The power dissipation across the resistor is similar to that of the full wave circuit for a minimum power dissipation rating of 300mW. Since the reference voltage remains unchanged, the minimum voltage rating of the capacitor is 15V. Due to the half-wave rectified signal being off for half of the period, the capacitor at the input to the LDO would need to be larger in comparison to the full wave circuit for the capacitor to discharge slower when the MOSFET is open for half of the period. Adjusting the capacitor value in LTSpice with size and cost as a consideration and the calculation for C1 as the baseline, the optimal capacitance to meet these criteria is 220μF. The minimum voltage rating of this capacitor would still have a minimum voltage rating of 6V. Table 4-2 shows the Bill of Materials listing the chosen components for the design utilizing the half-wave rectifier.

Table 4-2: *Bill of Materials Utilizing Half-Wave Rectifier*

Count	RefDes	Value	Description	Size	Part Number	Manufacturer	Per Unit Cost $	Total Cost $
1	R2	20kΩ	Resistor, Surface mount, 0603, 3/8W, ± 0.1%	0603	PHP00603E2002 BBT1	Panasonic	$0.61	$0.61
1	R1	100kΩ	Resistor, Surface mount, 0603, 1/5W, ± 0.5%	0603	ERJ-PB3D1003V	Panasonic	$0.18	$0.18
1	C2	220uF	Capacitor, Electrolytic, SMD, 6.3V, ± 20%	6.6mm x 6.6mm	ECE-V0JA221WP	Panasonic	$0.10	$0.10
1	C3	1uF	Multilayer Ceramic Capacitors MLCC - SMD/SMT 6.3volts 1uF X5R 10%	0402	C0402C105K9PA CTU	Kemet	$0.10	$0.10
1	C1	4uF	Capacitor, Electrolytic, Through Hole, 50V, ± 10%	6.3mm x 13mm	TE1302.1-E3	Vishay/Sprague	$1.56	$1.56
1	D1	-	Rectifiers 400V 1a Rectifier Glass Passive	4.75 mm x 2.95 mm	S1G	On Semiconductor	$0.22	$0.22
1	M1	-	MOSFET N-CH 240V 375MA SOT223	6.3mm x 6.7mm	BSP89,115	Nexperia	$0.53	$0.53
1	U1	-	LDO Voltage Regulator, 3uA, Vin = 20V, Vout = 3.3V	2mm x 2mm	LT3009ESC8#TR MPBF	Analog Devices/Linear Technology	$2.49	$2.49
1	U2	-	Gate Driver High & Low Side Driver	3mm x 4.9mm	LTC4440A-5	Analog Devices/Linear Technology	$2.33	$2.33
1	U3	-	IC OPAMP VFB 1 CIRCUIT 8SO	0.189mmx 0.228mm	LT1357 CS8#TRPBF	Analog Devices/Linear Technology	$2.45	$2.45
1	P1	-	CORD 18AWG NEMA1-15P - CBL 3.28'	3.28' (1.00m)	223053-01	Qualtek	$1.57	$1.57
1	L1	-	LED RED CLEAR 5MM ROUND T/H	10.10mm x 5mm	CP41B-RFS-CM0P0EE4	Cree Inc.	$0.15	$0.15

Chapter 5. Simulation Results and Analysis

The simulation tool of choice was LTSpice because of its availability of different parts and ease of use. Figures 5-1 and 5-2 show both the full wave and half wave rectified circuit designs. Since we used LTSpice, most of our components are ADI components. In the full wave rectifier circuit, single diodes were used in place of a single rectifier IC for simulation purposes. Also, in a real world setting our source would be an AC wall outlet using a two-pronged cable. Furthermore, our LED output is modeled as a 10mA load on the output of the linear regulator.
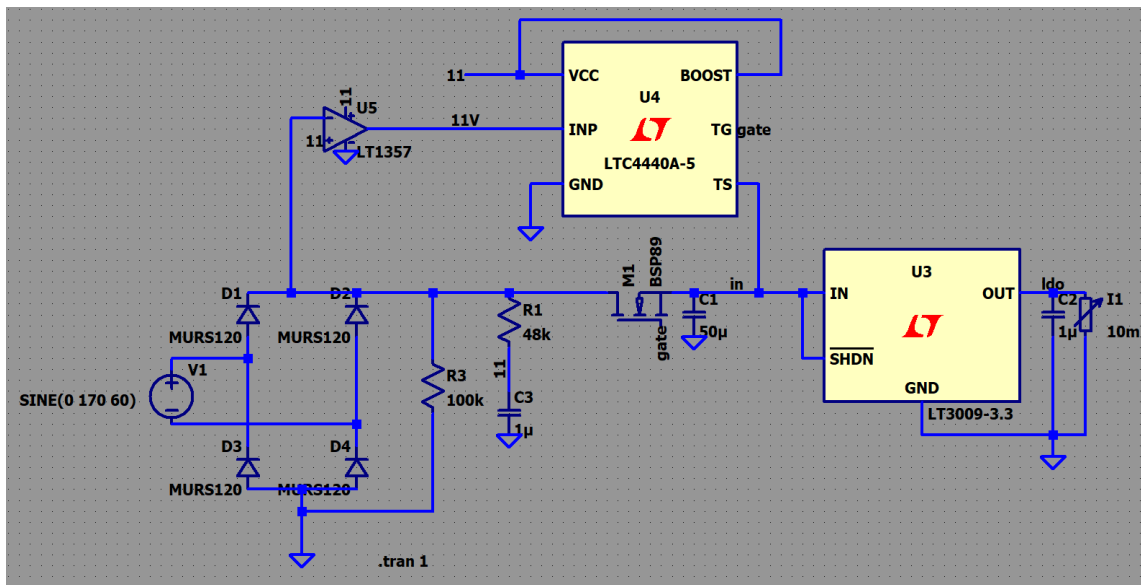

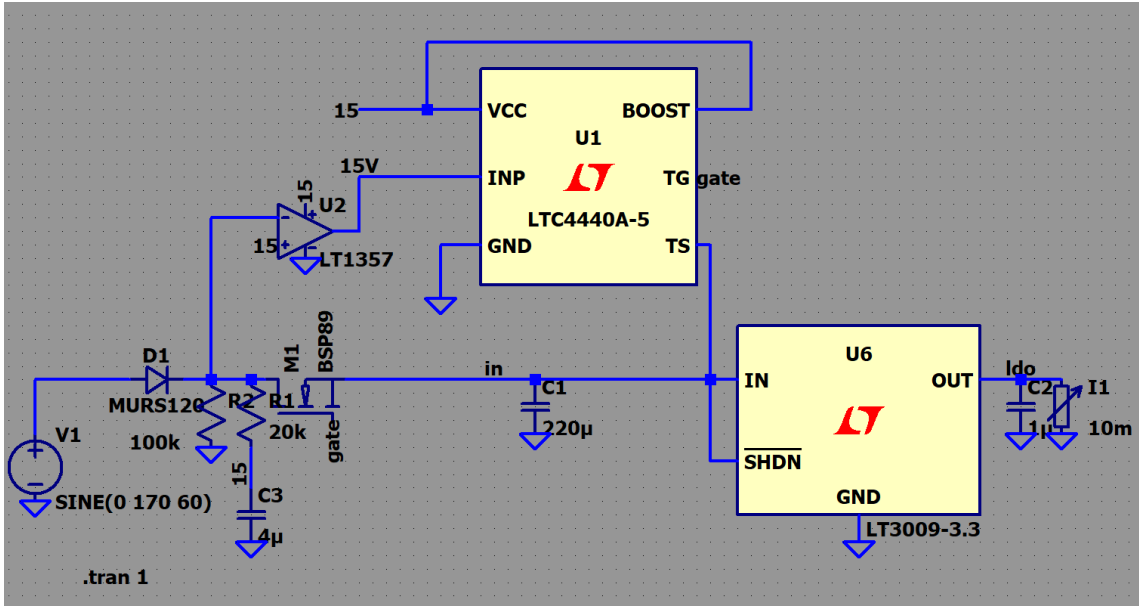**Figure 5-1:** *LTSpice Simulation of Full Wave Rectifier Circuit*

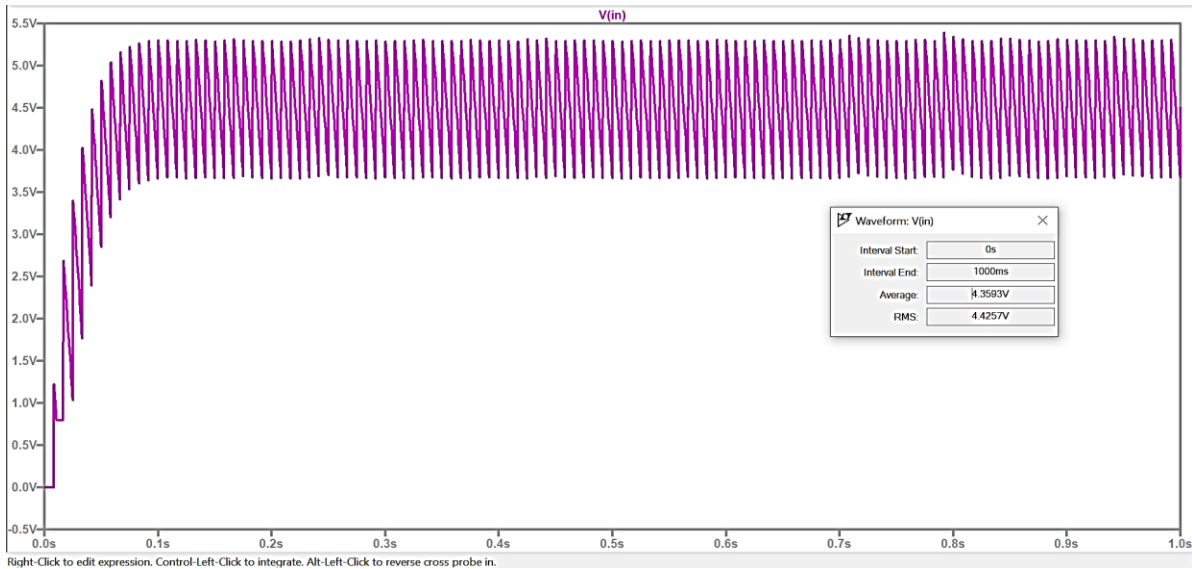**Figure 5-2:** *LTSpice Simulation of Half wave Rectifier Circuit*

Figure 5-3: *Input Voltage to the LDO (Full wave)*

In Figure 5-3, the input to the LDO of the full wave circuit has an average voltage of 4.35V which is needed for the LDO to regulate the voltage to 3.3V at 10mA. When the gate voltage shown in Figure 5-4 is low, the input capacitor discharges. The input voltage has ripple due to the charging and

discharging of the capacitor on the input of the LDO. To reduce this ripple voltage, the capacitor value was increased until the ripple was acceptable. With the small voltage ripple of the input voltage, the LDO can output a constant 3.3V.

When the switch turns on and off, there is a small ripple on the output of the LDO as seen in Figure 5-5. The ripple of the output voltage is 0.6%.
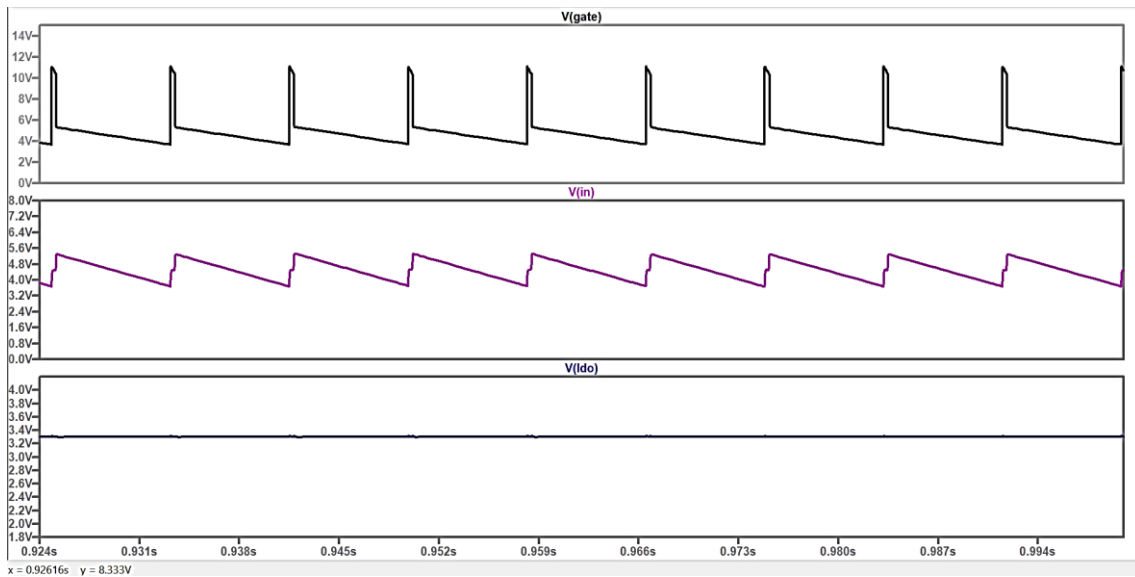

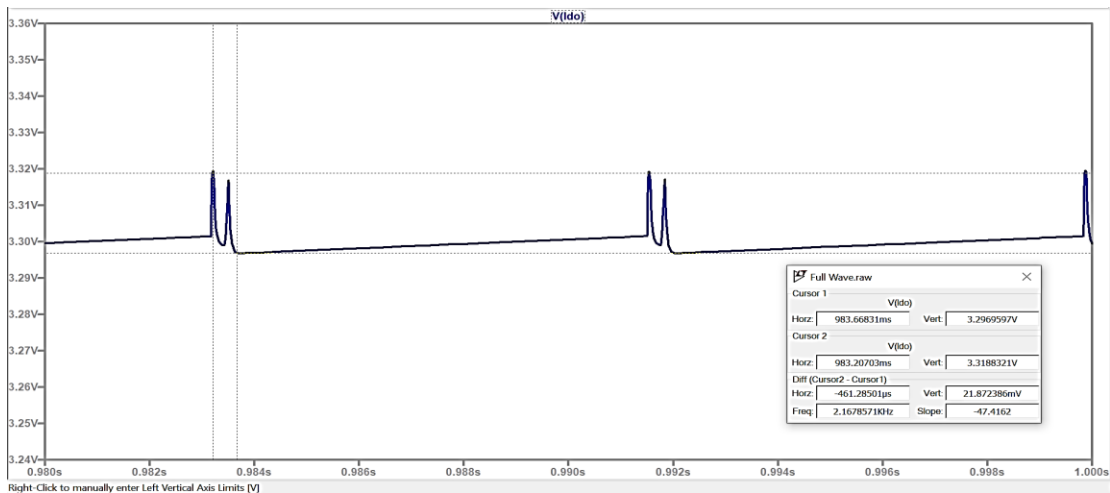**Figure 5-4:** *Gate Pulse, Input/Output Voltage (Full wave)*

Figure 5-5: *Output Voltage Ripple (Full wave)*

The transient response of the circuit is an important factor in determining the value of the input capacitor. A faster transient response directly correlates to a smaller capacitance value. However, this would lead to a larger ripple to the input of the LDO, which could prevent the LDO from regulating the output voltage correctly. With the capacitance of 47μF, the transient response of this circuit is 58.4ms with an input voltage between 4-5V as shown in Figure 5-6.
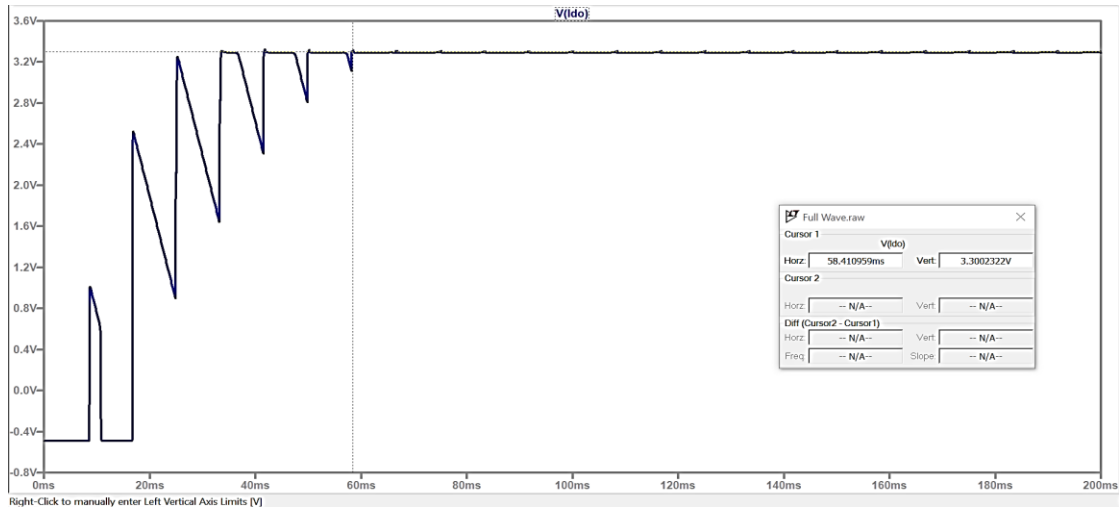

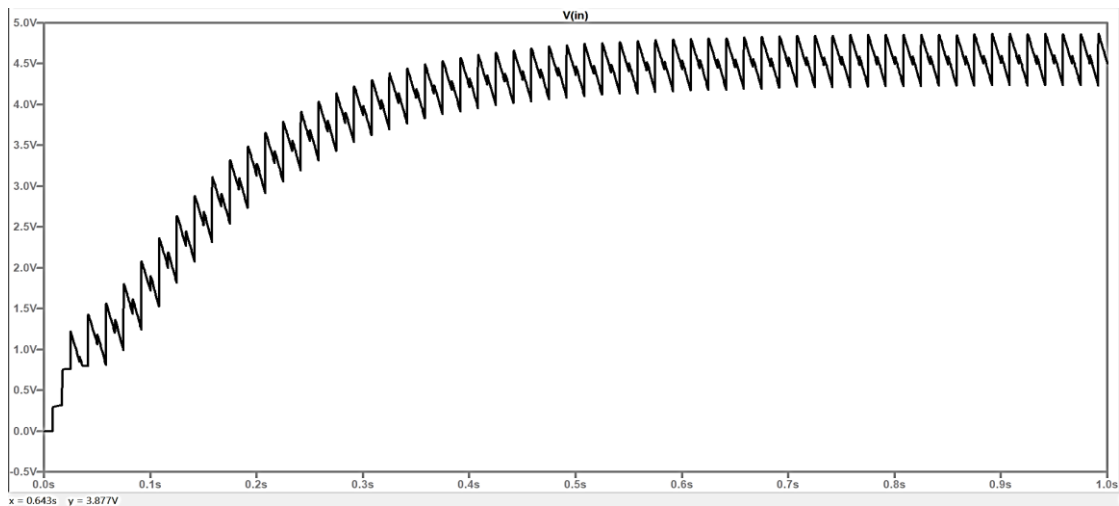**Figure 5-6:** *Transient Response of Full wave Circuit*

Figure 5-7: *Input to the LDO (Half Wave)*

In Figure 5-7 the input to the LDO has an average value of 4.35V. This voltage threshold is needed to allow the LDO to properly step down the input voltage to the desired output of 3.3V at 10mA. The waveforms in Figure 5-8 show the gate pulse and the input and output voltage of the LDO. The only difference in the operation of the halfwave and full-wave circuit is that a larger capacitance is needed on the input of the LDO. This is due to the half wave rectified waveform only being on for half of the period of a full wave rectified waveform. To have the same output a larger capacitance is needed to hold the voltage on the input.
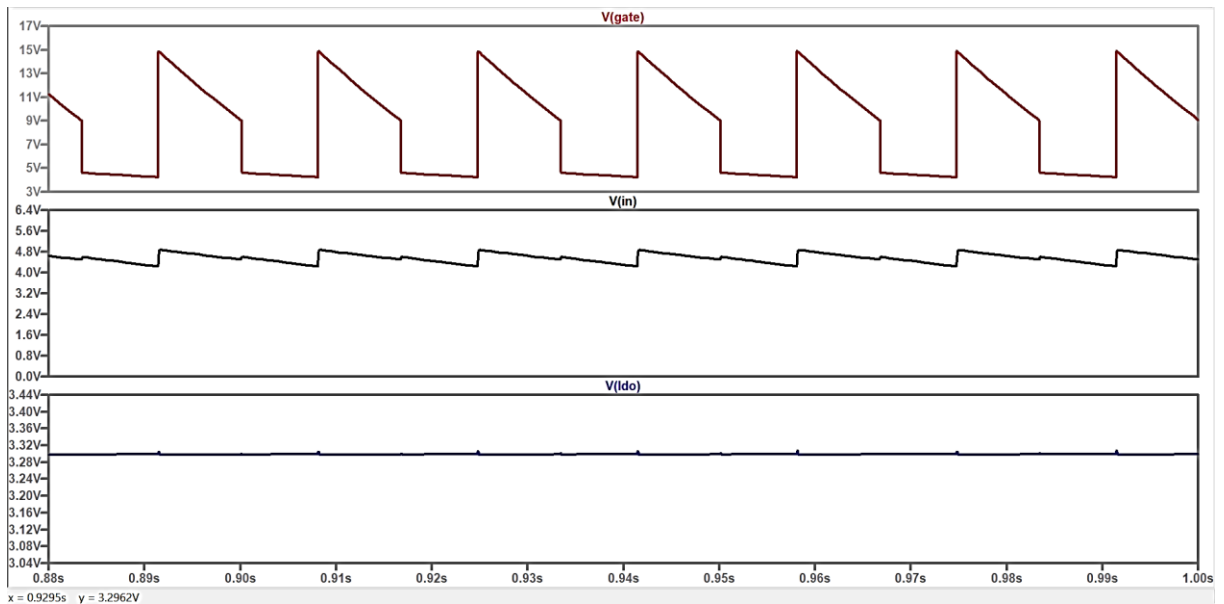
Figure 5-8: *Gate Pulse, Input/Output Voltage (Half wave)*

The waveform in Figure 5-9 shows the output voltage ripple which is 0.29%. This little bump on the output is caused by gate switching noise. Figure 5-10 shows the transient response of our design. It takes about 250ms to start properly regulating the output voltage, which is considerably longer than the full-wave circuit. The full-wave circuit only takes about 50ms to start regulating properly.

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Figure 5-9: *Output Voltage Ripple (Half Wave)*

Figure 5-10: *Transient Response (Half Wave)*

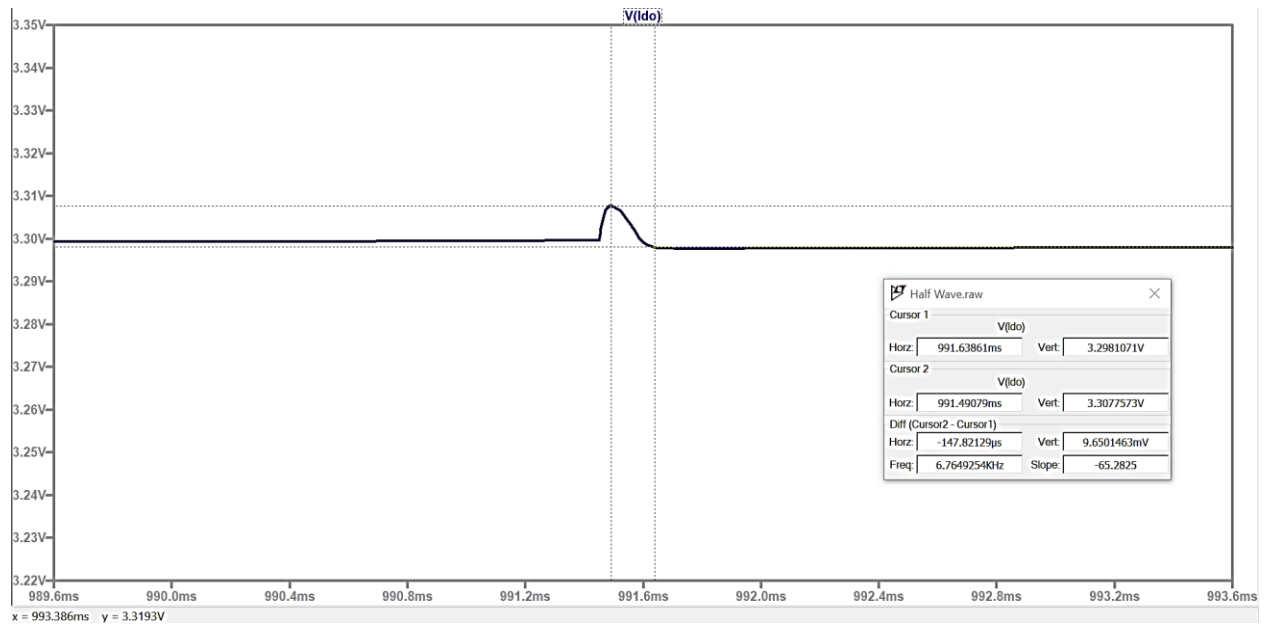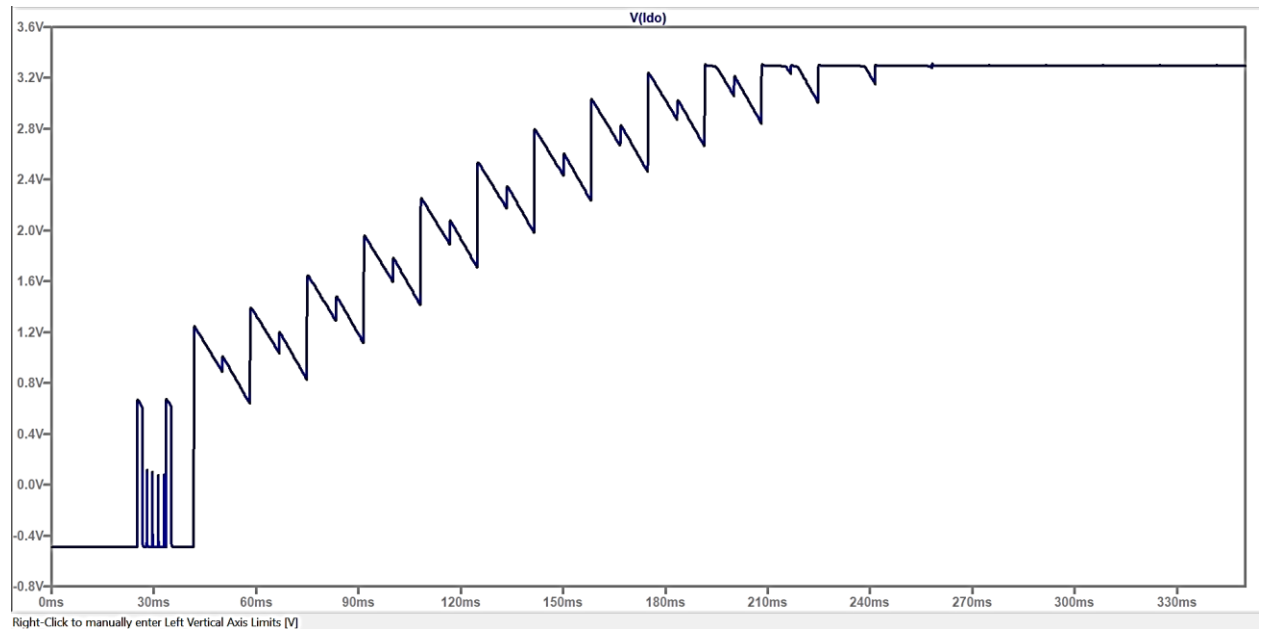**Table 5-1:** *Efficiency of the LDO*

	Full wave	Half wave
Pout	32.994 mW	32.987 mW
Pin	45.952 mW	45.662 mW
Efficiency	71.8%	72.24%

Table 5-1 lists the efficiency of the LDO in our design. Our initial design calculations estimated the efficiency of the LDO to be 66% for both designs. Here you can see that the efficiency of the LDO is actually higher than expected. This is because the input voltage is actually lower than the predicted 5V that was used in calculations. Also, the efficiencies of both the half wave and full-wave circuits are relatively the same due to the similar input voltages.

When looking at both designs, each has their own benefits and drawbacks. The full-wave circuit would need a smaller capacitor to save on both cost and board size and would have a faster transient response upon startup. The half wave circuit would need a diode to rectify the signal instead of a rectifier chip which would save in cost and complexity of the layout. Knowing that a half wave circuit is on for half of the duty cycle of a full-wave circuit, a larger input capacitor was to be expected. Though calculations showed the input capacitor of the half wave to be close to that of the full wave, the simulations reflected the need for a *larger* input capacitor. A high side driver was utilized to produce a clean PWM signal such as one from a pulse width generator. However, the driver produces a nonlinear pulse shown above to provide voltage and current for the MOSFET to turn on and off.

Chapter 6. Conclusion

In this project, we implemented a clipping circuit followed by a Low-Drop-Out regulator (LDO) to convert voltage from a wall outlet ($170V_{Peak}$) to 3.3V to power a DC load such LED. In simulation, we determined the circuit design and components necessary to implement the proposed AC-DC converter. Hardware construction to test the functionality of the proposed circuit did not take place due to the coronavirus pandemic causing campus and all the labs to be closed. However, we completed the hardware design by choosing the components needed to construct a prototype. The hope is that a future senior project could use the design to construct the actual hardware prototype of the proposed converter.

A major selling point of this design was that it does not include any bulky magnetic components such as a transformer to step down the AC voltage and an inductor used in a Buck converter as an energy storage. Because of this, the design should theoretically be small in form factor and more cost effective. However, this goal could not be demonstrated due to the absence of a hardware prototype which could not be constructed due to the pandemic.

The proposed design requires relatively large value capacitors in order to store the voltage after the rectification and the switch. This may constitute a trade-off compared with the conventional design which uses magnetic components. Another potential downside of the proposed design is the availability of the LDO which must be able to handle relatively high rectified AC input voltage of $170V_{Peak}$. However, as technology advances availability of high voltage LDO may not be an issue anymore in the future.

There are two variations for this design: a half wave or full wave rectifier. To save on the cost of a larger input capacitor and gain a faster transient response, the full wave rectifier would be a more ideal design to implement. For a smaller form factor and more cost effect solution, the

half wave rectifier may be a more ideal design to implement. Depending on the application of this design, these benefits and drawbacks would first need to be considered. Though the efficiency of an LDO is typically less than that of a buck converter, for small loads and low headroom voltage the efficiency tradeoff is minimal. Also, our design considers power dissipation in the LDO itself. If the LDO was given the rectified wall AC input instead of the 5V input proposed in our design, the efficiency of the LDO would be much less and the heat dissipated by the device would be much higher. This further implies the need for a cooling method such as heat sinks or a fan. From this point of view, the proposed design should yield a low-cost overall system by avoiding the use of heat sinks for the components or a fan.

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Appendix A. Analysis of Senior Project Design

Project Title: LDO + Clamping Offline Power Supply

Student's Name: Elizabeth Davis

Student's Name: Timothy Jeong

Advisor's Name: Taufik

• **Summary of Functional Requirements**

The LDO + Clamping Offline Power Supply is a non-traditional way to convert wall power to ($170V_{Peak}$) to a low output voltage and current (3.3V at 10mA) to power a small LED. Unlike most offline power supplies, this design will incorporate an LDO in order to eliminate the use of an inductor in the design. Also, a transformer is not used to step down the input voltage to the LDO. Instead, a switch will be used to control the input waveform and clip it to an allowable voltage (approximately 4-5V). These two factors ultimately allow for the form factor of the entire design to be quite small in comparison to other power supplies on the market today. It will also be more cost effective because the design removes some of the more costly parts.

• **Primary Constraints**

The main challenge of this project was that the design portion of it was impacted by the shutdown of lab facilities due to the coronavirus pandemic. This ultimately affected our ability to test and build a physical design. As a result, we were only able to complete a simulation of our proposed design. Another challenge was that our design was an entirely new idea, so finding references for this project proved to be difficult at times. However, we were able to break up the main idea of our project into smaller ideals and find references for those.

• **If manufactured on a commercial basis:**

This project was meant to be a proof of concept rather than an actual commercialized product. Once the design is constructed in hardware and tested then it could move on to be applied in a commercial setting.

• **Environmental**

As with any electronic device that is manufactured, it is important to note that the use of natural resources can have a detrimental effect to the environment. However, this project aims to reduce the number of components needed to convert wall power to low power output. It will directly use natural resources such as silicon and ceramic among other things in the manufacturing stage. When the project is actually implemented for use it will use wall power which could come from a variety of sources whether it be renewable or non-renewable.

• **Manufacturability**

Due to the shutdown of lab facilities, this project was not able to be manufactured and tested for its reliability. In different circumstances, this project would not be difficult to be manufactured due to the simplicity of this design. All of the components are readily available from manufacturers in the US and China.

• **Sustainability**

With the use of this project being implemented inside for the use of powering LEDs, there would be little to no maintenance for this project. With this design powering LEDs for a short period of time, there would be little concern for the components interacting with the high voltage. With this design of an offline power supply, this project uses less components and natural resources to

produce a similar output as a traditional offline power supply. Due to the shutdown of lab facilities, this project was not able to be manufactured, so there are currently no upgrades that could be made on this design.

• **Ethical**

There are many ethical considerations to think about when proceeding forward with this project. One major thing to consider is the fact that this design is currently not out on the market. To ensure that our design will work according to specifications and desire from the consumers, we will have to be careful in ensuring that each component works properly in our design. Our customers will be relying on us to deliver a complete product that they would be able to use in their homes. Also, another thing to consider is that the whole purpose of the project is to create an offline power supply that is more affordable compared to existing products. So, in order to deliver on that promise, we will have to closely look at the market price of other offline power supplies and price ours significantly lower. This will ensure that we price our product at an affordable rate to the customer. Another thing to consider is that this project will be handling high voltages from wall outlets. This mainly brings attention to the safety of the customer. To make sure that our product is safe, we will need to clearly mark hazards to the customer when handling wall plugs. Also, in our design we should make an effort to make sure that every component is rated correctly for the voltage, power, and current that it is supposed to handle. Furthermore, we should pick components that are reliable while keeping our production costs down.

• **Health and Safety**

The safety of the consumers is accounted for in the design of this project. With the use of high voltage and current from the wall, all of the components need to be rated for high voltage and current. With the use of high voltage, the consumers would need to be informed on how to properly operate this product.

• **Development**

In our design of this project, we had to learn control circuit techniques to implement the clipping portion of the design. We fully created and simulated our own control circuit to turn on and off the switch to let the allowable 4-5V be the input to the LDO. Also, we utilized a high side driver while doing this. A high side driver is a new component that had not come up in our previous power electronics courses. The high side driver was utilized to boost both the voltage and current of the gate signal going to the switch.