Senior Project Report

Investigating Efficiency of AC Direct Drive of LED Lighting

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EE462-12

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Abstract:

This project explores the rapidly-expanding area of AC direct drive for LED lighting. AC LED driving does not use typical DC-DC converter-based driving but uses semiconductor switches and a linear regulator to activate a number of LEDs proportional to the input voltage at any given time. This allows bulky, expensive magnetics to be eliminated from the system. The goal of this project was to develop a flexible simulation of a common AC LED system to find areas of significant power loss and attempt to improve them. This allows future versions of an AC LED system to start with major loss areas in mind, reducing development time and increasing performance. Systems tested included a three-stack binary switching system, a four-stack step-up switching system, a four-stack binary switching system, and a five-stack binary switching system. Through each simulation, the common theme was that the loss of the linear regulator was the dominant loss of the system. It was found that as the number of switches (and therefore switch states) increased, the loss of the MOSFET could be reduced significantly by reducing the voltage dropped across it. With three stacks using binary switching, MOSFET loss was 22.4W, or 29% of input power. With five switches, the MOSFET loss was reduced to 333mW, or less than 1% of input power.

Chapter 1 : Introduction

Efficiency in energy usage is defined as a ratio of energy output to energy input. This definition holds true at a larger scale, when discussing energy use on a societal level. An energy-efficient process is one that yields the same or more output for less energy input. It is important to separate energy efficiency from energy conservation. Energy conservation is usually abstaining from using energy for a process, rather than doing that process more efficiently [1]. One example of this would be working in a room that has natural sunlight instead of using a lamp. The lamp is not more efficient, it is simply used less.

Energy is created through many different processes, some of which are renewable and some which are not. A renewable energy source is "one that that can be easily replenished" [2], and a nonrenewable source is one that cannot. Since the majority of the United States' energy comes from nonrenewable sources (see Figure 1-1), using that limited energy efficiently is becoming more and more important.

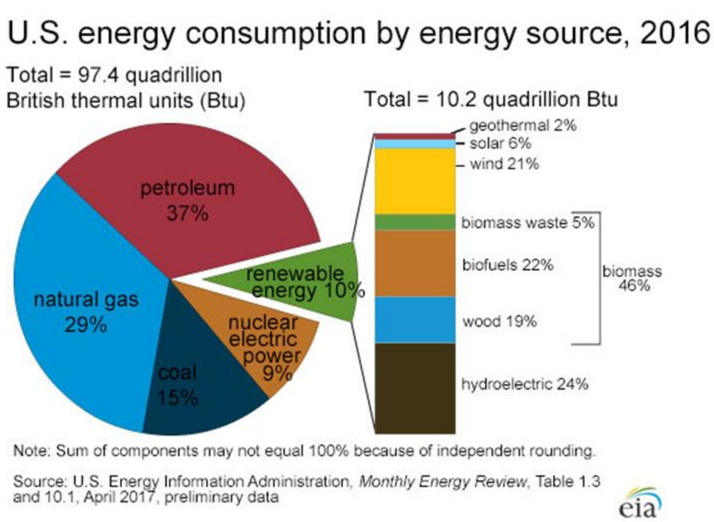

Figure 1-1: Energy consumption in the US by energy source. [2]

Energy efficiency is a topic discussed often now, with continually growing concerns about climate change, as well as increased energy costs and shrinking nonrenewable reserves. Many homeowners, for example, improve their home's efficiency by upgrading windows, insulation, appliances, and/or lighting. Better insulation and windows help improve heat and air conditioning efficiency, and new appliances and lighting solutions increase electrical efficiency [1]. Some states have created energy efficiency resource standard plans (EERS) to reduce the growth of electricity consumption over time. These programs use financial incentives or non-performance penalties to encourage efficient energy use in the state [3]. These plans are usually updated, and goals are expanded as they are met.

One significant category of energy use is lighting. The US Energy Information Administration estimates that the residential and commercial sectors of the United States used 279 billion kilowatthours of electrical power for lighting in 2016. That was 10% of the energy used in those sectors and 7% of the United States' total energy consumption [4]. The most popular lighting solutions are incandescent, fluorescent, compact fluorescent (CFL), and LED (light emitting diode). According to the US EIA, most households have a mix of these bulbs, where CFL and incandescent are the most popular [5]. In commercial buildings, over 90% of lighting is standard fluorescent, as seen in Figure 1-2. Also, in Figure 1-2, note that CFL use has increased over time and incandescent use has declined [6]. This is a common move from a less efficient to more efficient light bulbs to save energy and money.

Since 2013, LED bulb efficiency has exceeded typical CFL efficiency, with some exceeding 100 Lumens/Watt. Originally, LED bulbs were the most expensive but as prices come down, LED bulb shipments have increased from 9 million units in 2011 to 45 million units in 2013 [7]. Since they have higher efficiency, diminishing prices, and longer lifetime, LED bulbs are becoming increasingly common option to save energy and money.

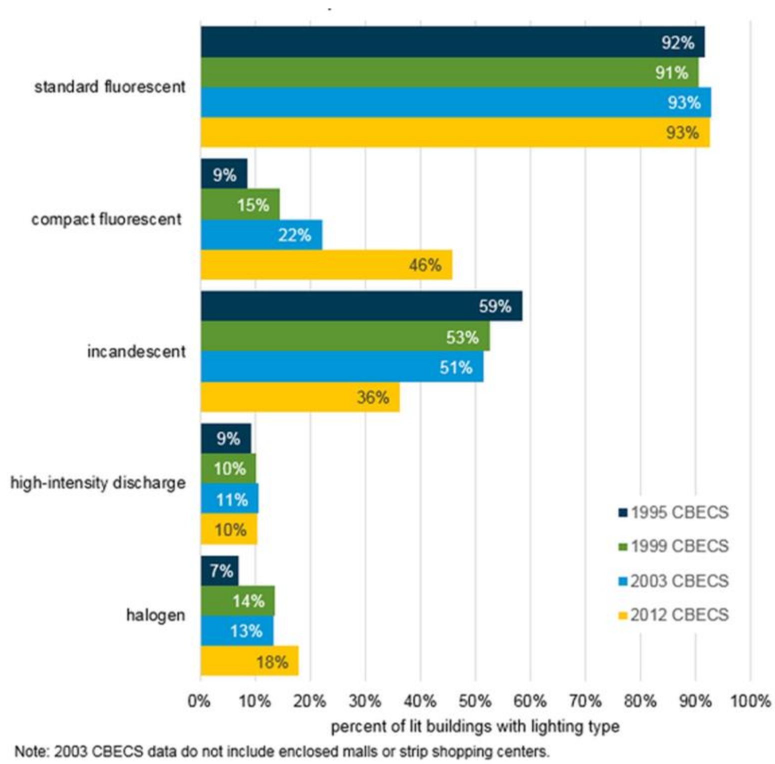

Figure 1-2: Light bulb use by type in commercial applications, from US EIA study [6].

Chapter 2 : Background

The use of LEDs for lighting is a small proportion of residential lighting and an even smaller portion of commercial lighting, but the number of LED bulbs used is increasing [8]. Some legislation is encouraging the shift to LED. The Energy Independence and Security Act of 2007 (EISA 2007) raised efficiency standards for 60-watt bulbs, effective in 2014, that incandescent bulbs could not meet. It is not expected that any company would attempt to make a more efficient incandescent bulb, since it is a mature technology with less room for growth than CFL or LED. EISA 2007 also set a minimum 45 lumens/watt efficiency standard effective in 2018 that is expected to eventually eliminate incandescent and halogen bulbs, forcing the market towards higher efficiency CFL and LED technologies [8]. In 2017, California's Title 24 will require household bulbs to exceed efficiency of 45 lm/Watt, power factor of 0.9, and rated life of 15,000 hours. These requirements will also push the market towards CFL and LED technologies [8].

Tables 2-1 and 2-2 show a selection of projection data about CFL and LED bulbs, respectively. These projections show that CFL bulbs, while efficient and inexpensive now, have less room to grow than LED bulbs. CFL efficiency, lifespan, and price are projected to improve slightly, but much less than LEDs. This demonstrates the expected push towards new LED technology and the need for innovation in the field to create these more efficient, longer lasting, and cheaper lighting solutions.

Table 2-1: A selection of projection data showing the expected growth of CFL technology in residential spaces [8].

CFL Bulbs		
	2015	**2040 (projected)**
Efficiency (lumens/Watt)	68.9	78.0
Typical Bulb Price	$2.03	$1.79
Average life (1000 hours)	10.0	11.3

Table 2-2: A selection of projection showing the expected growth of LED bulbs in residential spaces [8].

LED Bulbs		
	2015	**2040 (projected)**
Efficiency (lumens/Watt)	93	161
Typical Bulb Price	$7.53	$2.00
Average life (1000 hours)	25	50

Since LEDs operate with a DC current, most lighting solutions use an AC to DC converter to drive the LEDs. This can consist of a rectifier, followed by either a single stage with power factor correction (PFC) or two stages. These stages are switching DC to DC converters (such as a buck or boost) with large inductors and capacitors required. In a single stage solution, PFC maintains a good input characteristic with input current in phase with voltage, at the cost of larger flicker at the output, even with large filtering capacitors. A two-stage system has the first stage handle PFC, while the second reduces flicker, at the cost of adding a second stage. Large capacitors are still needed, as well as two inductors, which is a size issue in a bulb form factor [9]. Switching power supplies have the advantage of being very efficient, but the need for large electrolytic capacitors shortens the lifespan of the device. Even though LEDs and controllers have a lifespan of as much as 50,000 hours, the electrolytic capacitors have a much shorter life, which becomes the limiting factor of the device [9]. The size of capacitors and inductors/magnetics can be reduced by increasing the switching frequency of the system, but this in turn can degrade efficiency because of switching losses (which are proportional to switching frequency). Increased frequency can also increase EMI noise. These issues have driven researchers to find other methods to drive LEDs which better match the longevity of the devices and provide a simpler solution.

One such solution is referred to as AC direct drive of LEDs. In general, this method consists of using switches to control strings of LEDs and turning on a number of LEDs proportional to the input voltage at any given time. A linear regulator is typically used to dissipate any leftover voltage and help keep the input current in phase with the voltage for improved power factor. A rectifier is still used at the input to have purely positive voltage swings into the system. These systems are typically cheaper, simpler, and less noisy than DC to DC switching converters and solve some of the issues presented [10].

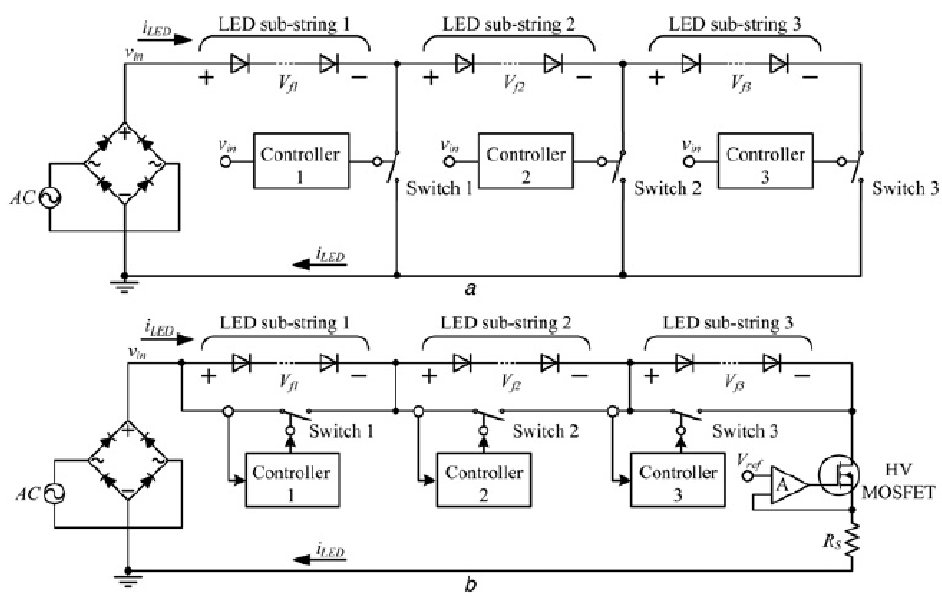

Figure 2-1: A series switching system (top) and parallel switching system (bottom) [11].

In most common AC LED systems, there are two ways to place the switches, and two different schemes to switch them. Systems either have the switches in parallel with the LED strings, or in series with the LED strings. In a parallel switching configuration, the switch is used to direct current away from the LED string. This can be seen in Figure 2-1 (bottom). In a series configuration, the switch connects each string to ground in order (Figure 2-1, top) [11].

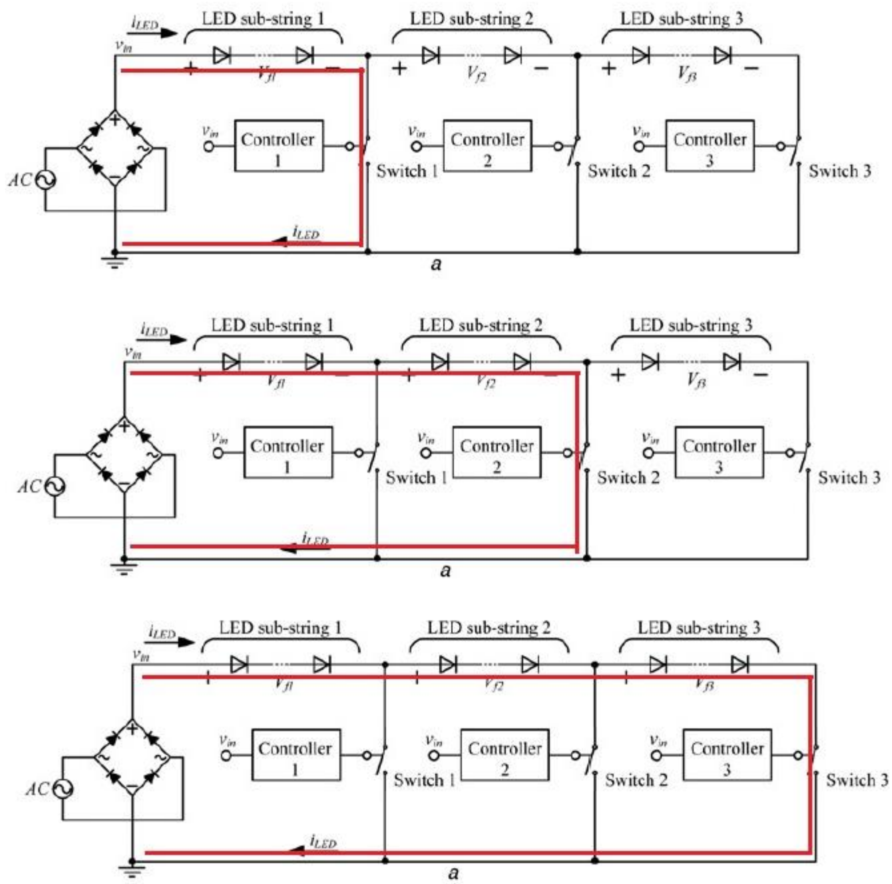

Figure 2-2: Augmented diagram showing three switch states in a series configuration [11].

Within these two methods of configuring switches, there are two main ways to switch the strings on and off. One, usually used with the series switch topology, is to turn on the strings in order as input voltage increases. This can be seen in Figure 2-2. As the input increases, more and more LEDs are turned on by turning on a single switch after the desired number of strings. This can be done in a parallel configuration as well, with simply the opposite logic (when switch is off, LEDs are on). One commercial example of this method is the Fairchild FL77944, which is close to an all-in-one IC that has internal MOSFETs in series with off-chip LEDs. The shunt regulator is also on board, and for lower power systems it does everything needed in a small package [12].

Table 2-3. Example of Switching Scheme for Parallel Topology

Switch State	Switch 1	Switch 2	Switch 3
1	0	0	0
2	0	0	1
3	0	1	0
4	0	1	1
5	1	0	0
6	1	0	1
7	1	1	0
8	1	1	1

The other switching scheme used is where the switches are altered in a binary counting method. This can only be used with a parallel topology since it necessitates the ability to turn on any one string or combination at any time. In a series topology, only a string and all below it can be turned on. In this binary switching, the switch states follow a standard truth table with 2^n (where n is the number of switches) states possible. See Table 2-3 for an example with three switches (note that a "1" refers to that set of LEDs being on, and the switch is off due to the negative logic of the parallel configuration). If the number of LEDs in each string doubles (2 in the first string, 4 in the next, etc.), then the number of LEDs on increases by one for each increasing switching state, which helps keep power factor and THD high (waveform is close to sinusoidal).

One commercial example of a parallel, binary switching configuration is using the Texas Instruments TPS92411 switch with the TPS92410 linear regulator. This semiconductor switch has a built-in MOSFET, but each switch is in its own chip. This allows for different size systems, built from a single building block. Most examples are systems in the under-50W range, but its scalability allows it to potentially be used for higher power [13].

This senior project aims to design and simulate an AC direct drive LED system, with topology based on the research done so far. It will be a modification of the parallel topology with binary switching, using the TI TPS92411 switching signals as a template. The objective is to design and simulate this system to analyze the best methods of improving efficiency and negotiate meaningful tradeoffs between them.

Chapter 3 : Design Requirements

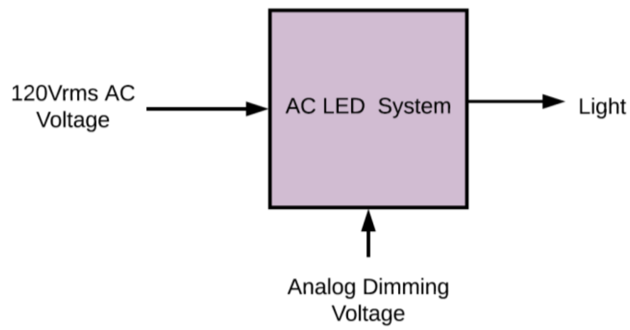

Figure 3-1: Level 0 block diagram of system.

The level 0 diagram of this AC LED system as illustrated in Figure 3-1 shows the input is standard 120Vrms, 60Hz AC power, and the output is light from the LED array. Also possible is the analog dimming voltage, from 0 to 10V that can dim the brightness of the LEDs (if the TPS92410 is used). The system will be designed to have the highest efficiency. The system should have an output power of approximately 50W and improve upon efficiency. Possible applications for a higher-power system like this include stadium lights, parking lot lights, or gas station downlights.

At a finer level, Level 1 Block Diagram shown in Figure 3-2, the system can be broken into three main blocks: rectifier, switch/LED stacks, and linear regulator. The full bridge rectifier converts the line voltage so only positive swings go into the system. The switch/LED stacks consist of a TI TPS92411 "smart" switch and LED string. Each switch monitors for zero crossings to switch as the voltage increases in a binary order. This is done without another external controller or communication between the chips. To improve efficiency, the switching signals may be modified in simulation and would require a main controller to build. The on-board MOSFET opens or closes to steer current into or away from the LED stack. The Linear regulator monitors the rectified input voltage and modulates the gate voltage of the off-board MOSFET so that the input current shape follows the input voltage shape for improved power factor. The advantage of an off-board MOSFET is that it can be sized as needed for the rating of the system.

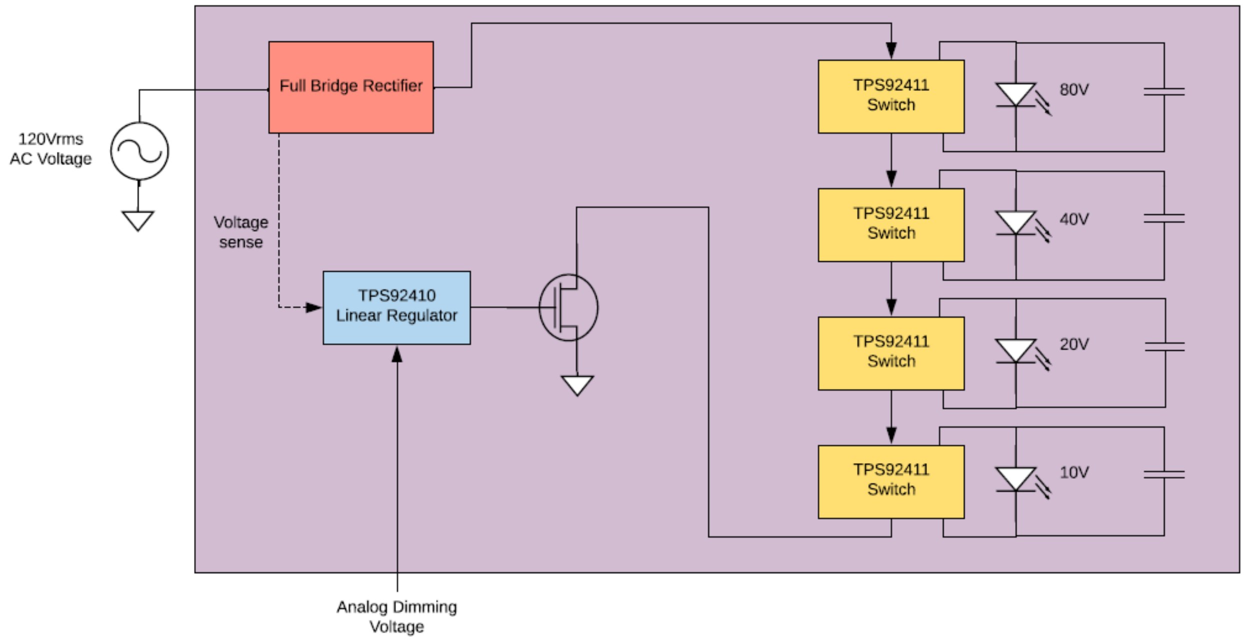

Figure 3-2: Level 1 system block diagram.

Technical Design Requirements:

The main goal of this project is to explore several variations of an AC LED system to identify the areas that can be modified for higher efficiency operation. The design will start with a TI reference design, but once the most significant areas of power loss are identified, modifications will be made to improve these deficiencies. This 50W reference design from TI achieved efficiency of 86.5%, PF of 0.97, and THD of 10.5%.

Table 3-1: Technical requirements of AC LED system.

Specification	Value	Justification
Input Source	120Vrms, 60Hz	This system will use the standard power found in the United States.
Efficiency	Greater than 85%	The reference design starts near 85% efficient, so high-loss areas will be identified and improved upon. This is the most important goal of the project.
Power Factor	0.9	High power factor ensures the system is not requiring excessive reactive power. This is ensured by the linear regulator.
THD	15%	Low THD is necessary to keep power quality high and not inject excessive harmonics into the grid.
Flicker	5%	Flicker is largely dependent on use. It is unacceptable in an office, but okay in a parking lot. The goal is to measure the flicker and see what can be done to improve it.
Size	N/A	Size is of no concern for this design, other than eliminating large input capacitors and inductors from a DC-DC system.

Chapter 4 : System Design and Simulation

As stated previously, the main goal of this investigation is to identify and attempt to improve the areas of this system with the most power loss to improve efficiency. Then, the advantages and disadvantages of each method can be compared. The designs tested will demonstrate a three-switch binary system, a four-switch step-up system, a four-switch binary system, and a five-switch binary system.

Methods/Assumptions:

To begin, a flexible simulation had to be created that allows the LED stack voltage, MOSFET sinking current, component choices, and switch signals to be adjusted for different methods. This is accomplished by using LTSPICE. Instead of a model of the TI TPS92411 switch, voltage-controlled switches with piecewise linear voltage sources (as controls) are used to allow for mimicking functionality of the TI chip and for custom switching schemes (see Figure 4-1). The TPS92411 datasheet states the built-in MOSFET has an R_{DSon} of 2Ω, so an on-resistance of the switch in the simulation is set at 2Ω as well, for a baseline and better approximation of the TI switch [14].

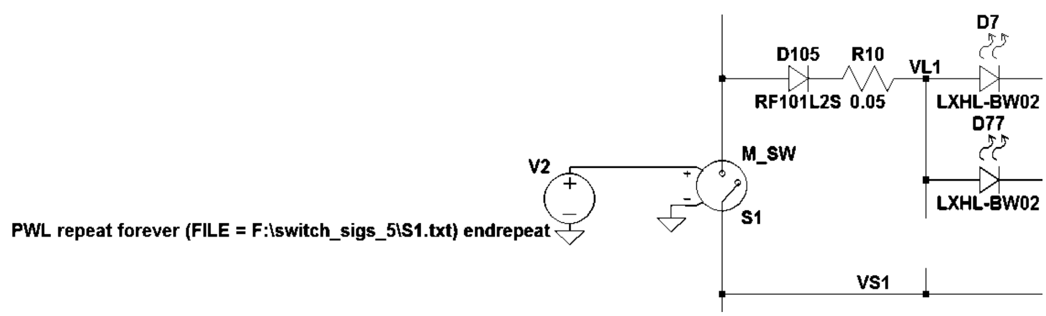

Figure 4-1: Example of a single voltage-controlled switch reading from a control file periodically.

For the linear regulator in the system, a design made from discrete components is chosen for maximal flexibility in variations of the baseline system [14]. It also allows for more analysis of the functionality than a chip that abstracts some of the function away. The goal of this regulator is to limit current through the branches of LEDs for a desired output power, as well as to improve power factor by ensuring the shape of the input current matches the shape of the input voltage. The regulator uses a resistive divider (R1 and R6 in Figure 4-2) to sample the input voltage, using large values for minimal current and loss. This voltage drives the gate of the current regulating MOSFET, with a feedback from a sense/current-limiting resistor between the source of the MOSFET and ground. This resistor is used to set the current through the MOSFET, and by extension the output power since this current is sent though the LED stacks. The MOSFET chosen is one which meets the voltage rating of 700V from the reference design, the Infineon IPB65R420CFD [15]. This regulator is used for all designs in this project, with changes to the source resistor to set the output power.

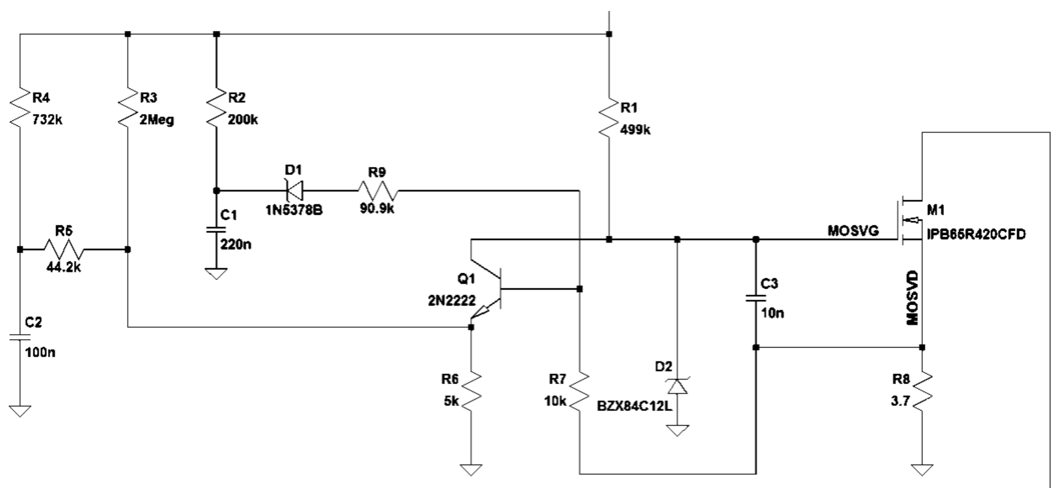

Figure 4-2: Discrete linear regulator used for all testing.

To generate the initial switch signals for some configurations, TINA TI was utilized. This program is capable of simulating a model of the TPS92411 but does not offer enough flexibility for the rest of the investigation in this project. By simulating the system with the same linear regulator and input in TINA, the timing of the switches could be measured and replicated in text files read by the piecewise linear sources in the main LTSPICE simulation. This file had the controls for one period of the rectified input and is repeated indefinitely. For variations built upon this baseline version, the piecewise linear switch signal files were modified manually. One example of a step-up style of switching scheme was tested to compare to the more common binary type using some hand calculations, outlined later in the appropriate design section.

The output power of each system had to be chosen to be a consistent value, to allow for more comparable results between different methods. Since the initial design is based upon a 50W TI reference design, a goal of approximately 50W was set for each system [15]. This represents a system on the higher end of AC LED systems easily created with one set of switches/LEDs, and higher power systems would likely have arrays of these blocks combined in parallel. To set this power, the output power was measured and the source resistor of the MOSFET was adjusted until the desired output power was reached.

The LED stack sizes are recommended by TI to be approximately 80V, 40V, 20V, and 10V (from stack one to four). This translates into twenty-eight, fourteen, seven, and four LEDs in each respective stack. In this simulation, a model for Luxeon LXHL-BW02 is utilized to approximate the LEDs in the TI system. For most simulations, the LED stack voltage was kept constant, except for the final design with five switches, where the stacks had to be reduced to create enough headroom for the fifth switch. This will be discussed further in the design section for that topology.

Data Collection Methods:

The same measurements are taken for each topology/switching method, to enable easy comparison between them. Some are simple waveform captures such as LED stack voltages (voltage across the switches/LED stacks), stack currents (current through each LED stack), piecewise linear voltage source signals, and MOSFET drain current and drain-to-source voltage.

Some other characteristics require calculations. Since efficiency is the most important focus of this project, the input and output power must be calculated, as well as power lost by the input rectifier, switches, MOSFET, and source resistor. All are calculated and then the average of the instantaneous power over a round number of periods is recorded. These are measured in simulation as follows:

$$P_{in} = AVG((V_a - V_b) * I_{source})$$

where V_a and V_b denote the voltage potential on either end of the voltage source in the input rectifier, and I_{source} is the current drawn from this source. The output voltage equation is given below:

$$P_{out} = AVG((V_{l1} - V_{s1}) * I_{R10} + \ (V_{l2} - V_{s2}) * I_{R11} + \cdots)$$

where V_{ln} is the voltage on the top of LED stack n (after the blocking diode and sense resistor), V_{sn} is the voltage on the bottom of LED stack n, and I_{R1n} is the current through sense resistor R_{1n} of stack n in series with the LEDs. This summation is completed for each stack in the given design, either three, four, or five stacks. The power absorbed by the rectifier is:

$$P_{rect} = AVG(V_{D1} * I_{D1} + \ V_{D2} * I_{D2} + \ V_{D3} * I_{D3} + \ V_{D4} * I_{D4})$$

where V_{Dn} is the voltage across rectifying diode n, and I_n is the current through rectifying diode n. MOSFET power loss can be calculated by:

$$P_{MOSFET} \ = \ AVG(V_{DS} * I_D + \ V_{GS} * I_G)$$

$$P_{RS} = \ AVG(V_S * I_D)$$

where V_{DS} is the drain-to-source voltage of the MOSFET, V_{GS} is the gate-to-source voltage, I_D is the drain current, I_G is the gate current, and V_S is the source voltage of the MOSFET.

Also captured is the input voltage and current, used to calculate power factor as follows, where I_{inRMS} is measured in simulation.

$$PF = \frac{P}{S} = \frac{P_{in}}{V_{inRMS} I_{inRMS}}$$

Finally, efficiency is calculated with the ratio of average output power to average input power.

$$\eta = \frac{P_{out}}{P_{in}}$$

Dominant Losses in the System:

The losses in this system are dominated by the rectifier diodes, the switches, and the linear regulator. The regulator (MOSFET and R_{source}) is the dominant loss in most cases, as would be expected from a linear regulator.

In this system, any voltage not dropped on the LEDs is dropped across the MOSFET. Since the current is regulated and set by the desired output power, the V*I losses on the MOSFET are solely a function of the voltage across it. By Kirchoff's Voltage Law, during a half cycle of the input:

$$V_{in} = 2 * V_{rect.\ diode} + V_{LEDs} + V_{MOSFET} + V_{Rs}$$

$$V_{MOSFET} = V_{in} - (2 * V_{rect.\ diode} + V_{LEDs} + V_{Rs})$$

The voltage drops from the rectifier diodes and source resistor are both a function of the current in the system, which is restrained by the output power requirement. Therefore, these are relatively constant. Recall:

$$P_{MOSFET}(V_{MOSFET}) \approx AVG(V_{MOSFET} * I_D)$$

Since the drain current is restrained by output power, power loss of the MOSFET is determined entirely by the voltage across it. This is, in turn, entirely determined by the number of switches, LED stack voltages, and switching signals. Since MOSFET loss is dominant, the only significant way to increase efficiency is to alter these aspects of a system. This is true for all configurations and will be observed throughout these tests. This is the motivation behind primarily testing different switching styles and not component types.

Configuration 1: Three-Stack, TI Binary Switching

The first configuration has three LED stacks, with a TI TPS92411-based switching style. The standard discrete linear regulator is used with a source resistance of 3.9Ω. This is summarized in Table 4-1 and Figure 4-3.

Table 4-1: Configuration 1 specifications.

Number of LED stacks	3
Switching style	TI Binary
Stack one size	90.5V, 28 LEDs
Stack two size	45.6V, 14 LEDs
Stack three size	23.2V, 7 LEDs
Stack four size	N/A
Stack five size	N/A
R_{source}	3.9Ω

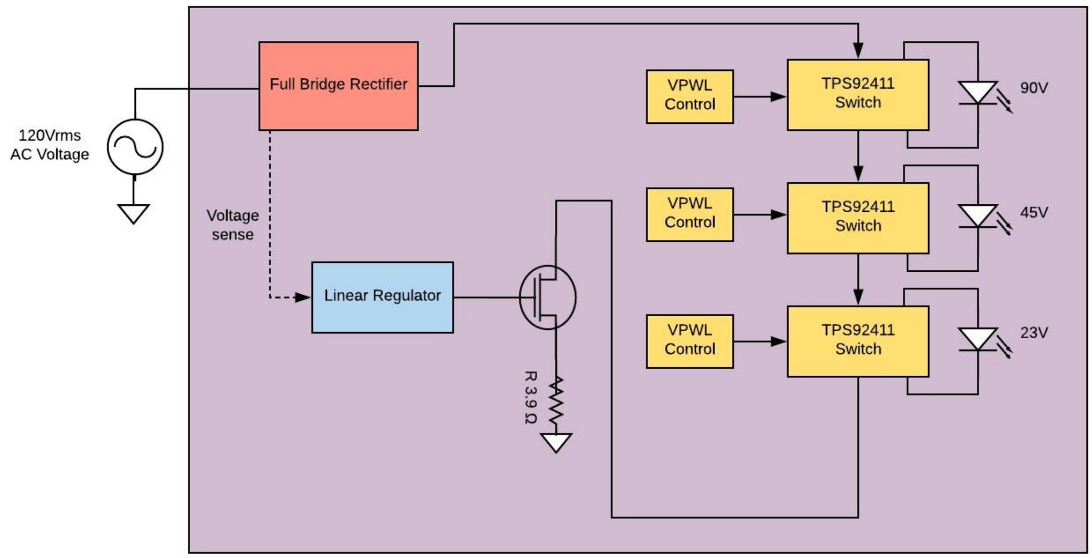

Figure 4-3: block diagram of configuration 1.

A TINA TI simulation is used to create the piecewise linear voltage source files, seen in Figure 4-4. This simulation uses the same linear regulator design. By copying this switching functionality into LTSPICE with piecewise linear sources and switches, the timings can be adjusted, and the results can be more easily analyzed.

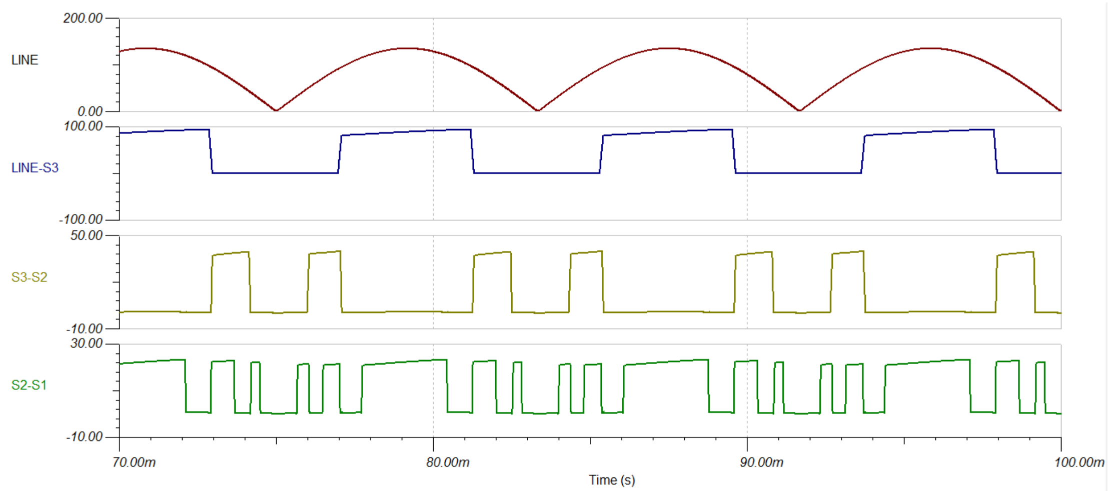

Figure 4-4: TINA simulation of three-stack system. This shows (from top to bottom) input voltage, stack one voltage, stack two voltage, and stack three voltage.

Figure 4-5 shows the signals from the piecewise linear control sources as well as the rectified input and total voltage across all three stacks. Notice the inverse logic of the switches, since a switch being on means current is diverted away from the LEDs in that stack. However, the signals do match the design and TINA simulation.

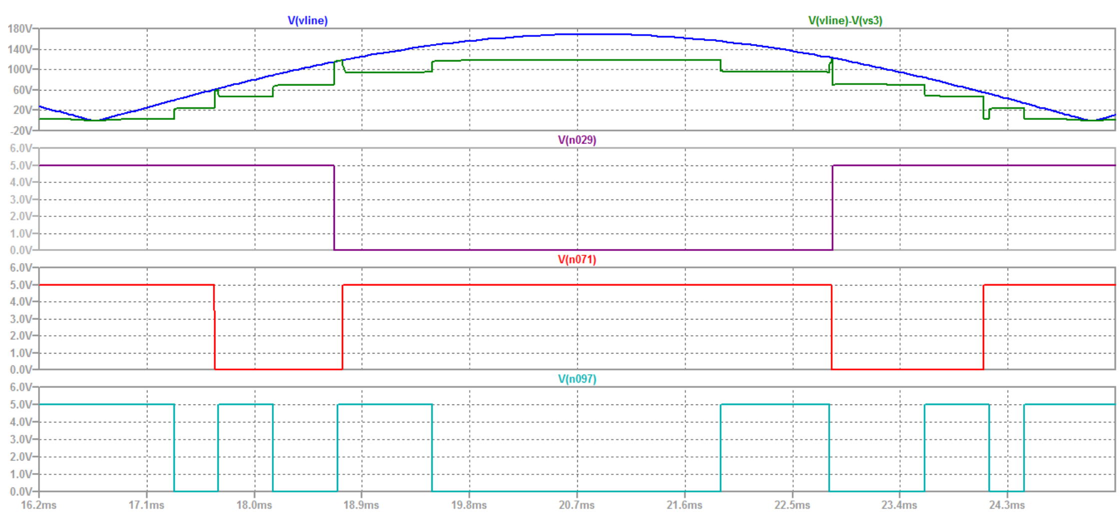

Figure 4-5: From top to bottom: Rectified input and voltage across all stacks, switch one control, switch two control, switch three control.

Also measured in the simulation is the stack voltages and stack currents (Figures 4-6 and 4-7). This indicates that the switch signals are functioning correctly and when the switch is on, there is near zero voltage across the stack (only the drop across the switch remains) and when the switch is off, the stack voltage rises to the appropriate level for the number of LEDs in the stack. Likewise, the current plot shows when the LEDs are on and when they are off. It also shows how the collection of stacks is sharing a total current set by the regulator.

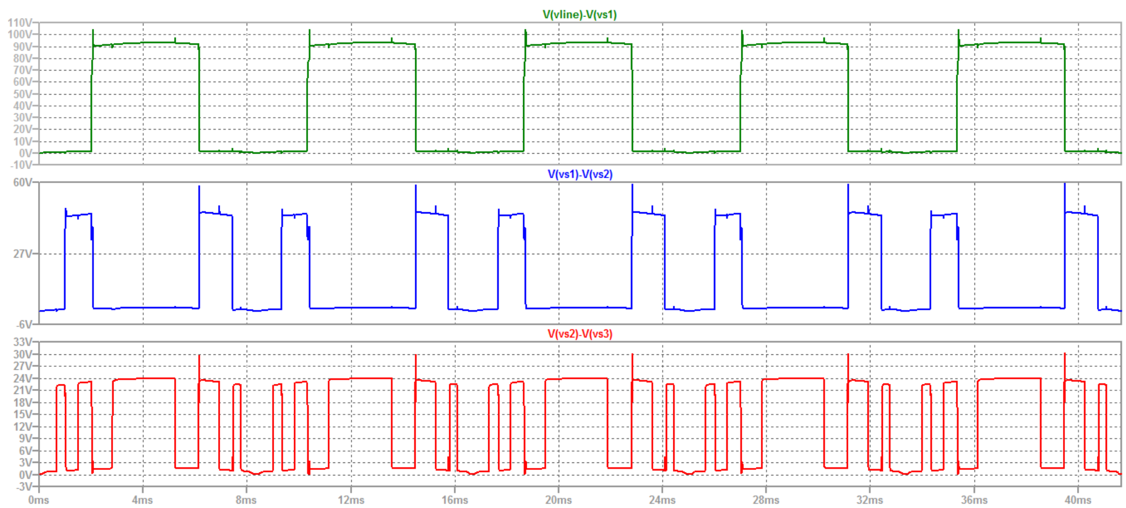

Figure 4-6: From top to bottom: stack one voltage, stack two voltage, stack three voltage.

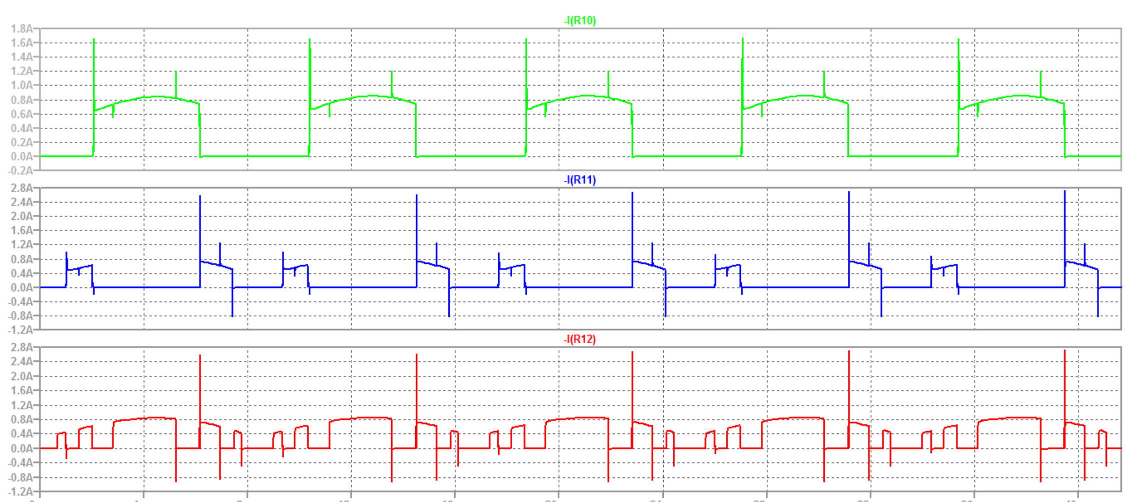

Figure 4-7: From top to bottom: stack one current, stack two current, stack three current.

This regulated current and the voltage difference between the LED stacks and rectified input can be seen in Figure 4-8, which shows the MOSFET drain-to-source voltage and drain current. The

MOSFET voltage takes on a triangular or sawtooth shaped waveform due to the squared-off nature of the total stack voltage and the sinusoidal input. In this version, the voltage across the MOSFET is large, with peaks as high as approximately 50V and an average of 31.6V.

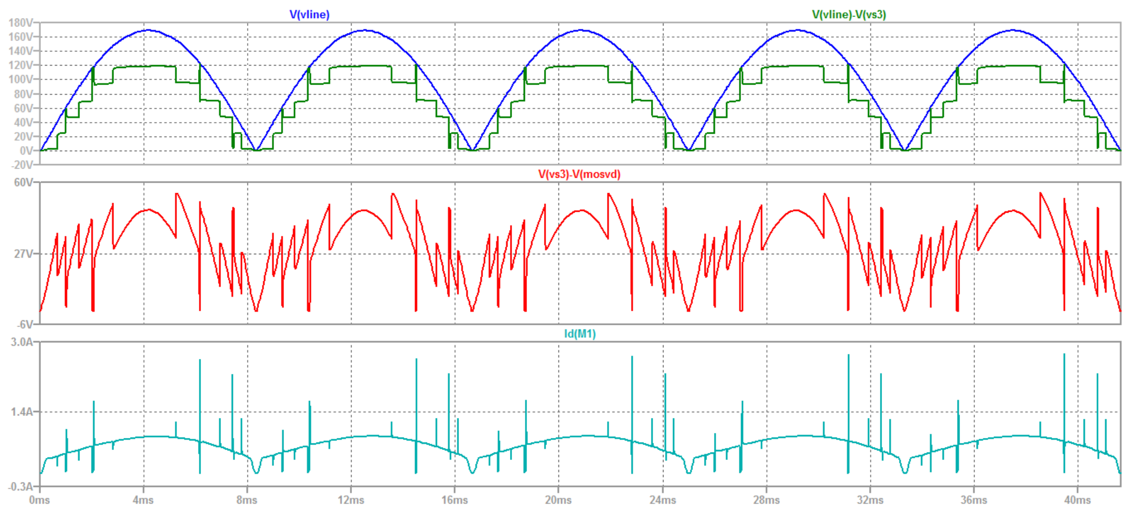

Figure 4-8: From top to bottom: Rectified input voltage and total LED stack voltage, MOSFET drain-to-source voltage, and drain current.

The input characteristic was measured next. Figure 4-9 shows the input voltage and current. Although there is some noise as expected from the switching, the overall shape follows the input voltage for improved power factor. In this configuration, the power factor is measured to be 0.983.

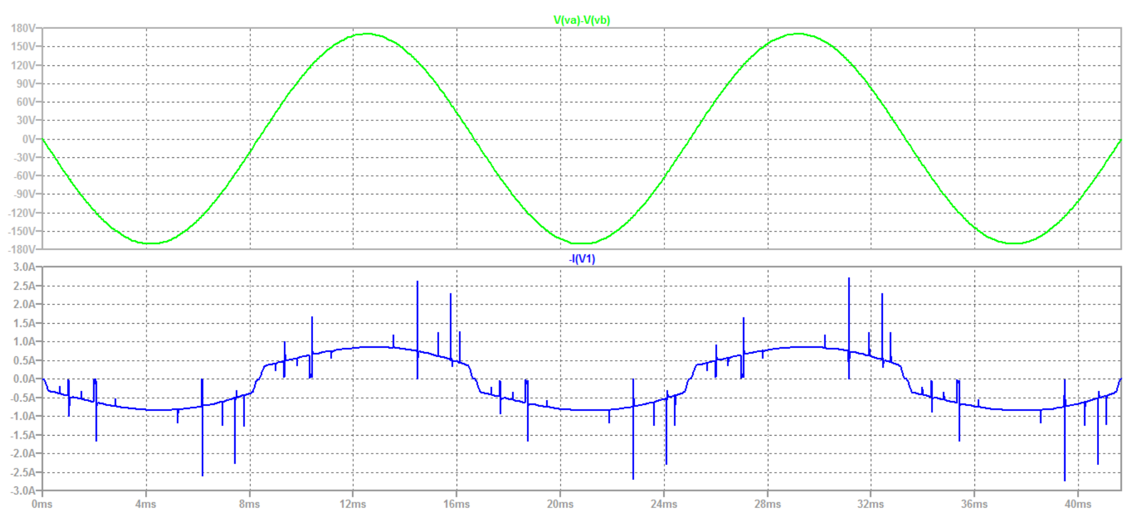

Figure 4-9: Input voltage (top) and input current (bottom).

Finally, the input power, output power, and power losses were measured as described in the "data collection methods" section. These are summarized in Table 4-2 showing that the dominant losses are from the linear regulator, particularly the MOSFET. This impacts the efficiency significantly, with an overall value of 65.24%.

Table 4-2: Power input, output, and loss in configuration 1.

P_{in}	78.984W
P_{out}	51.536W
P_{MOS}	22.362W
P_{RS}	1.734W
P_{RECT}	1.176W
P_{SW}	1.303W
η	65.24%

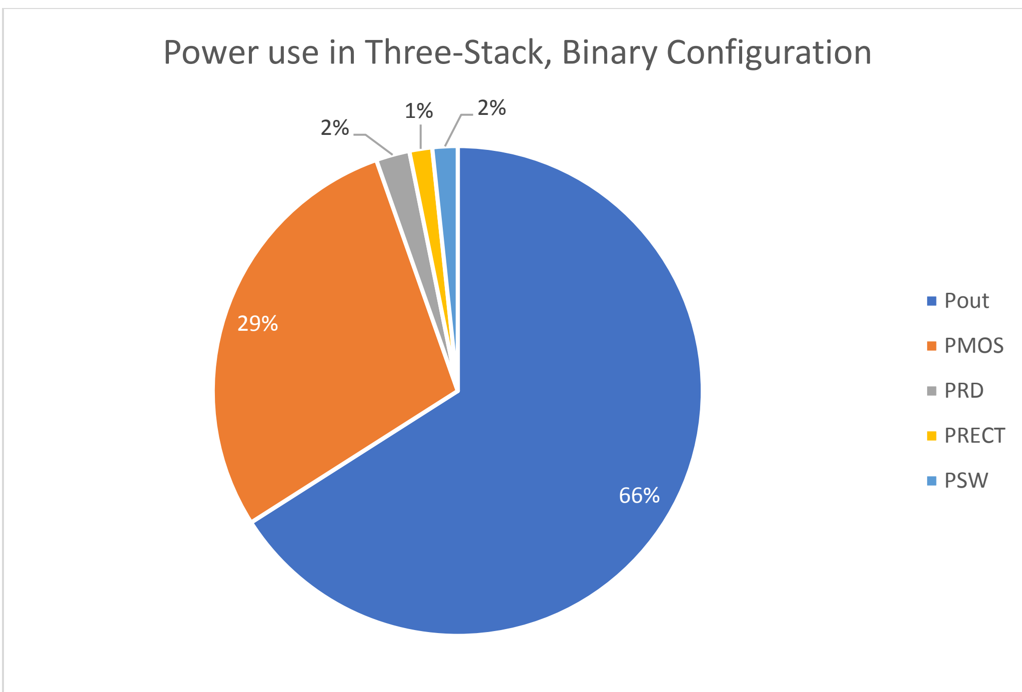

Figure 4-10: Pie chart representation of power use in configuration 1. Each power value is divided by the input power, so the chart demonstrates percent of input power used by each component.

Configuration 2: Four-Stack, Step-up Switching

This configuration uses four switches and a step-up style of switching. This means that when the input reaches a threshold high enough to turn on another stack of LEDs, that stack is added in. This creates only four different switch states. The standard discrete linear regulator is used with a source resistance of 4.3Ω. This is summarized in Table 4-3 and Figure 4-11.

Table 4-3: Summary of configuration 2.

Number of LED stacks	4
Switching style	Step-up
Stack one size	90.5V, 28 LEDs
Stack two size	45.6V, 14 LEDs
Stack three size	23.2V, 7 LEDs
Stack four size	13.2V, 4 LEDs
Stack five size	N/A
R_{source}	4.3Ω

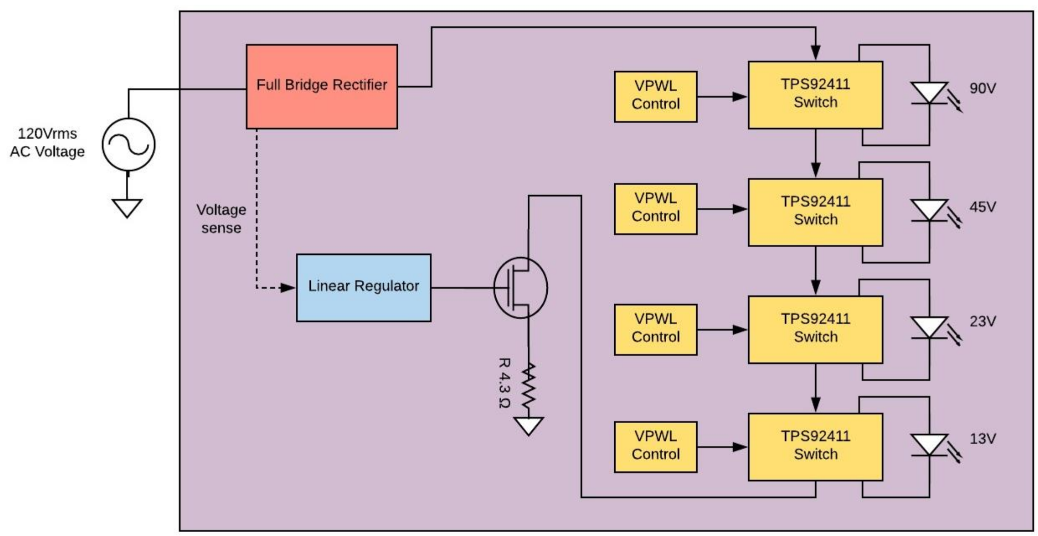

Figure 4-11: Block diagram representation of configuration 2.

The switch signal timing for this design was calculated by hand, by simply solving for time as a function of rectified input voltage. The input is known to be a rectified $120V_{RMS}$ sine wave, so the equation from 0ms to 8.333ms (one cycle at 120Hz) follows:

$$v(t) = 120\sqrt{2}\sin(2\pi 60t)$$

When time is solved for as a function of voltage, the following equation results:

$$t(v) = \frac{1}{2\pi 60} sin^{-1}\left(\frac{v_n}{120\sqrt{2}}\right)$$

where v_n is the voltage of an LED stack or combination of them. The four levels in this case will be 13V, 37V, 82V, and 159V. The highest peak cannot have all four stacks on, because it is larger than the peak of the input. This calculation creates the following table of times, in Table 4-4.

Table 4-4: Switch times and active LED stacks for configuration 2.

Voltage	0V	13V	37V	82V	159V	159V	82V	37V	13V	0V
Time	0ms	203µs	583µs	1.338ms	3.219ms	5.114ms	6.995ms	7.750ms	8.130ms	8.333ms
LED stacks on	none	4	4, 3	4, 3, 2	3, 2, 1	3, 2, 1	4, 3, 2	4, 3	4	none

Figure 4-12 shows the simulated version of these calculated switching signals. Again, they are logically inverted because to turn LEDs on, their respective switch must be off. Below this, as shown in Figure 4-13, is the stack voltages and currents demonstrating that the signals are successfully diverting current as desired.

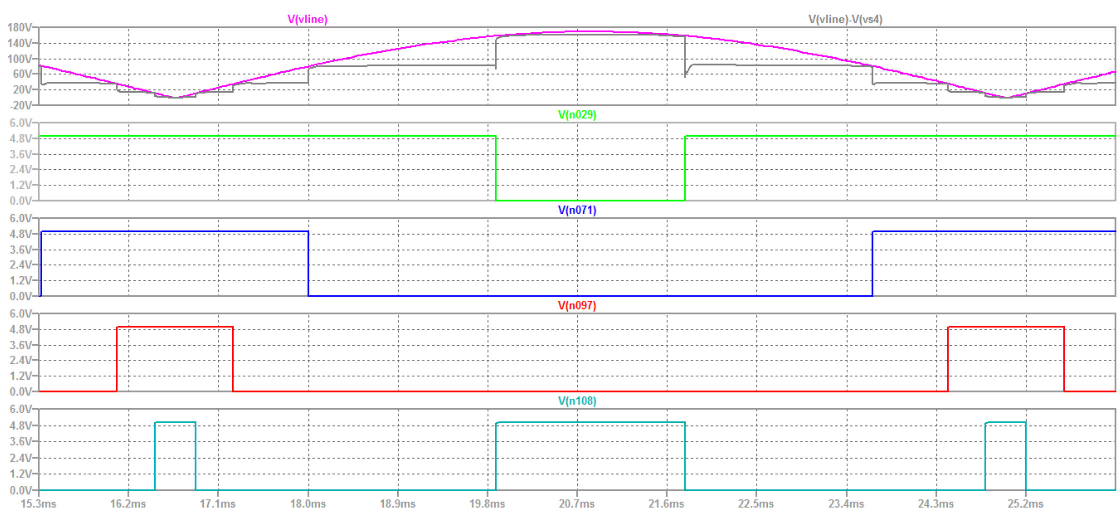

Figure 4-12: From top to bottom: rectified input voltage, switch control one, switch control two, switch control three, switch control four.

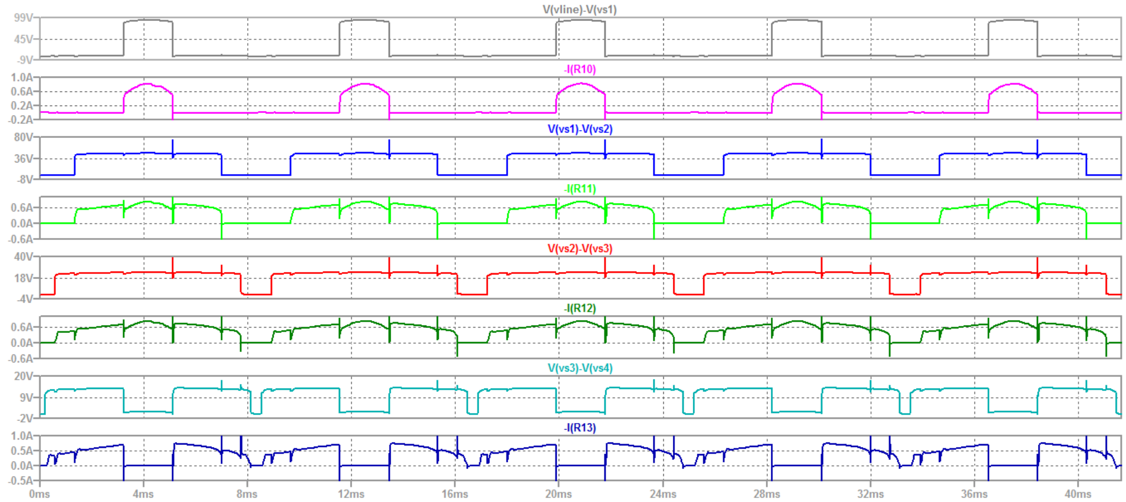

Figure 4-13: From top to bottom: stack one voltage, stack one current, stack two voltage, stack two current, stack three voltage, stack three current, stack four voltage, stack four current.

The difference between the rectified input voltage and the total LED stack voltage is dropped on the MOSFET and current-limiting resistor. This can be seen in Figure 4-14. As with the previous method, the voltage across the MOSFET is large, with an average of 22.2V. The addition of the fourth stack allows the total LED voltage to better match the input, but the step-up switching creates only four switch states, which is still too coarse to avoid large loss on the MOSFET, as in Table 4-5.

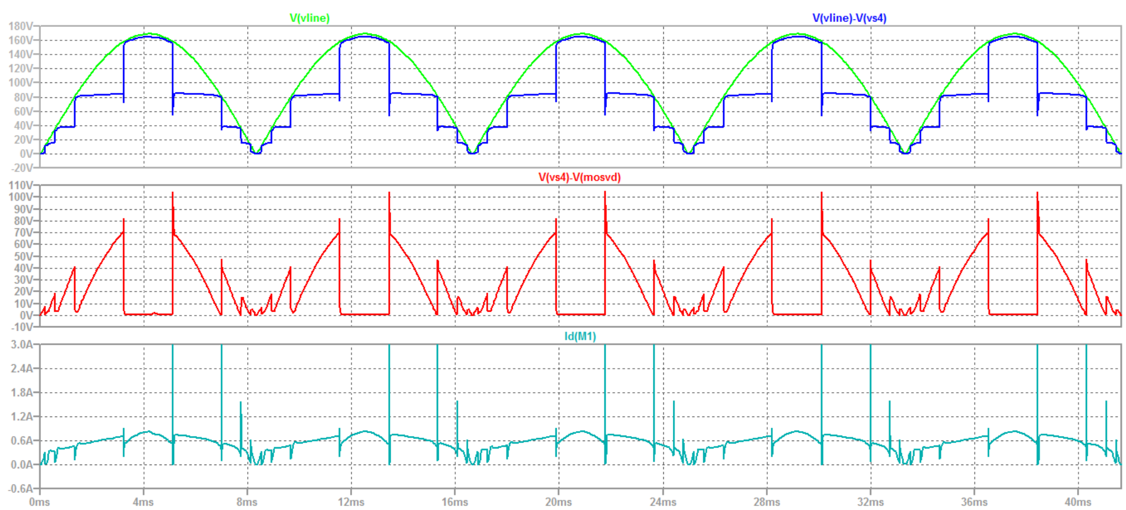

Figure 4-14: From top to bottom: rectified input and total LED stack, MOSFET drain-to-source voltage, MOSFET drain current.

The input characteristics of this configuration is demonstrated in Figure 4-15. Although there is some noise as expected from the switching, the overall shape follows the input voltage for improved power factor. In this configuration, the power factor is measured to be 0.980.

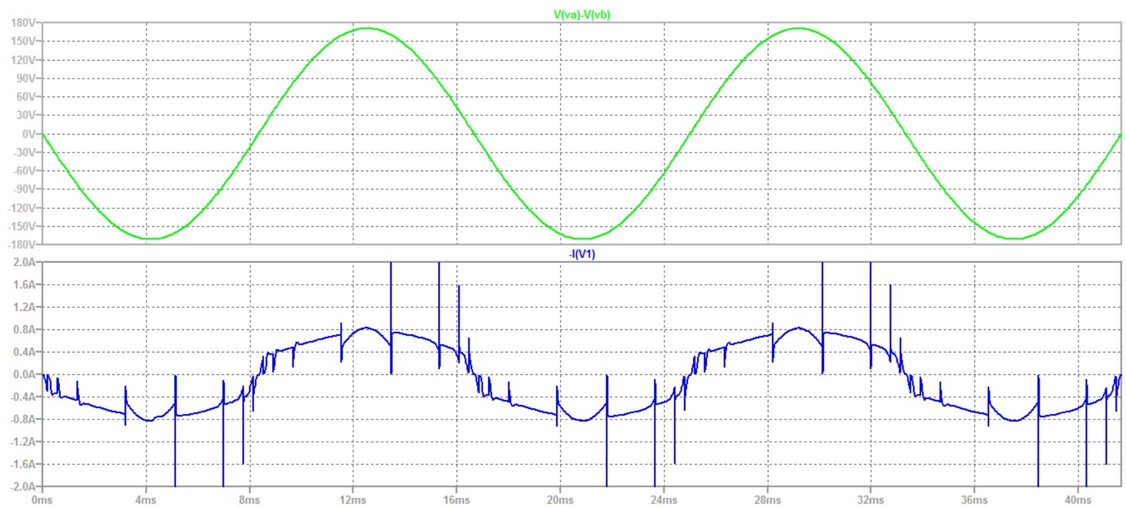

Figure 4-15: Input voltage and current for configuration 2.

Table 4-5 and Figure 4-16 show the distribution of power use and efficiency of configuration 2. MOSFET loss is reduced slightly due to the reduced voltage across it. The fourth switch allows the LED stack to more closely follow the rectified input voltage, but the low number of switch states still leaves large enough voltage drops to lose 20% of the input power on the MOSFET.

Table 4-5: Input, output, and lost power for configuration 2.

P_{in}	69.346W
P_{out}	51.140W
P_{MOS}	13.551W
P_{RS}	1.490W
P_{RECT}	1.018W
P_{SW}	0.818W
η	73.75%

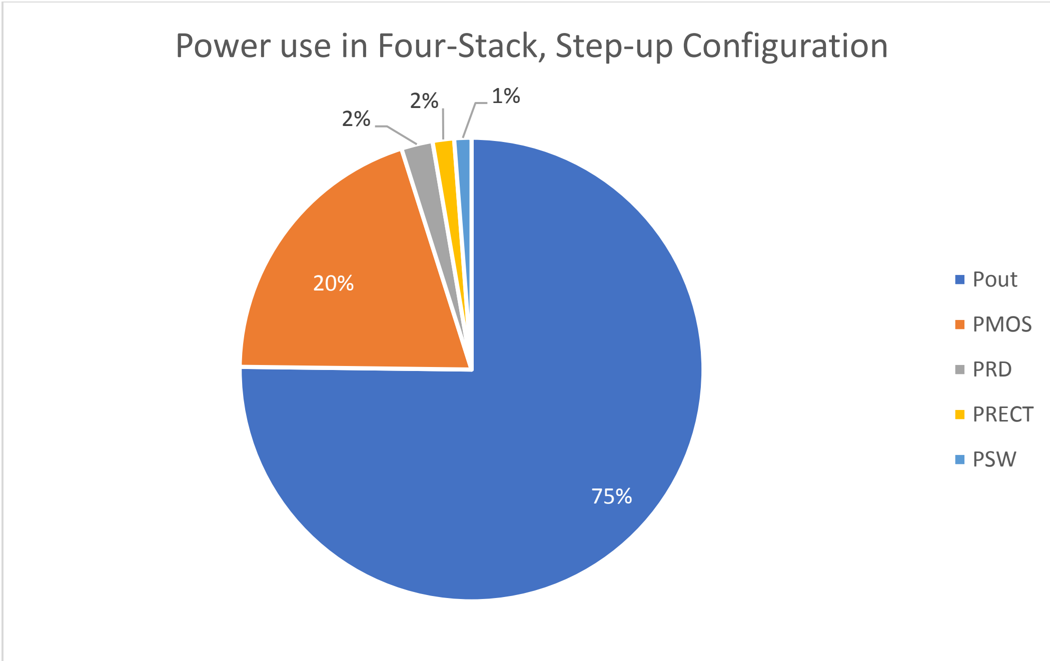

Figure 4-16: Pie chart showing percent of input power used for each component. MOSFET loss is still the dominant loss, although a smaller percentage than configuration 1.

Configuration 3: Four-Stack, TI Binary Switching

This configuration uses four switches and a TI binary style of switching. The standard discrete linear regulator is used with a source resistance of 5**Ω**. This is summarized in Table 4-6 and Figure 4-17. A TINA TI simulation is used to create the piecewise linear voltage source files, as with configuration 1.

Table 4-6: Summary of configuration 3.

Number of LED stacks	4
Switching style	TI Binary
Stack one size	90.5V, 28 LEDs
Stack two size	45.6V, 14 LEDs
Stack three size	23.2V, 7 LEDs
Stack four size	13.2V, 4 LEDs
Stack five size	N/A
R_{source}	5Ω

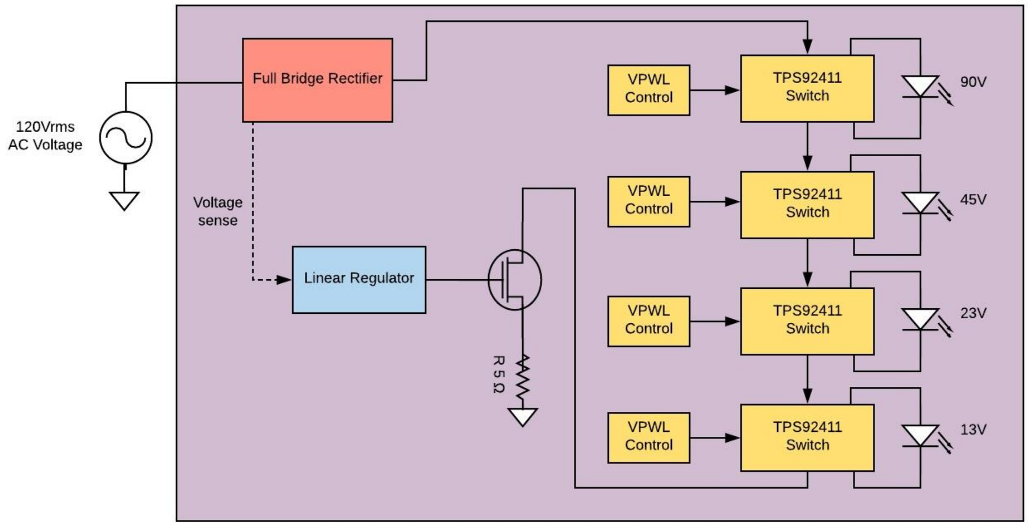

Figure 4-17: Block diagram description of configuration 3.

Figure 4-18 shows the switching signals based on the TI switching order. This replicates the TPS92411 functionality with four switches. This switching scheme creates more possible switch states, allowing the total stack voltage to more accurately follow the input voltage.

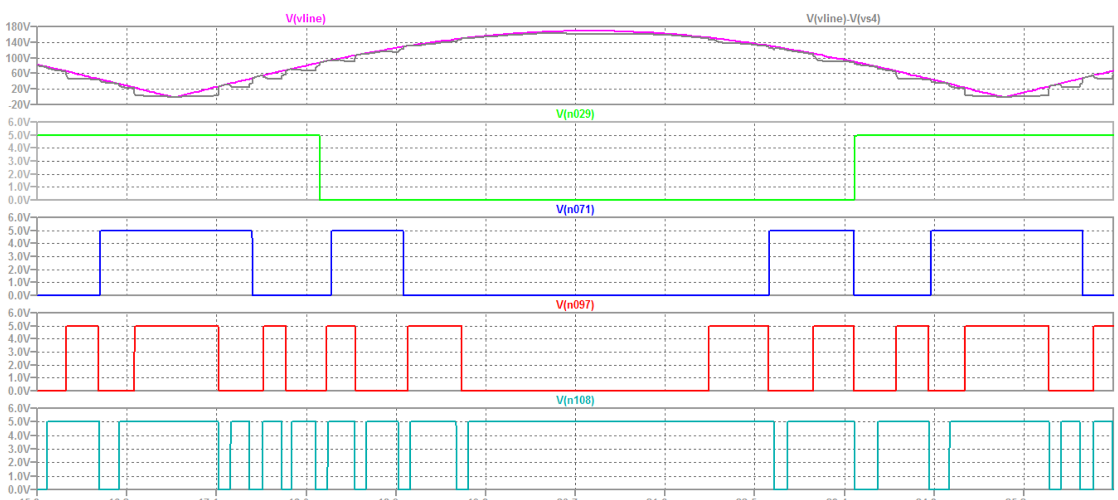

Figure 4-18: From top to bottom: rectified input voltage and total stack voltage, switch one control, switch two control, switch three control, switch four control.

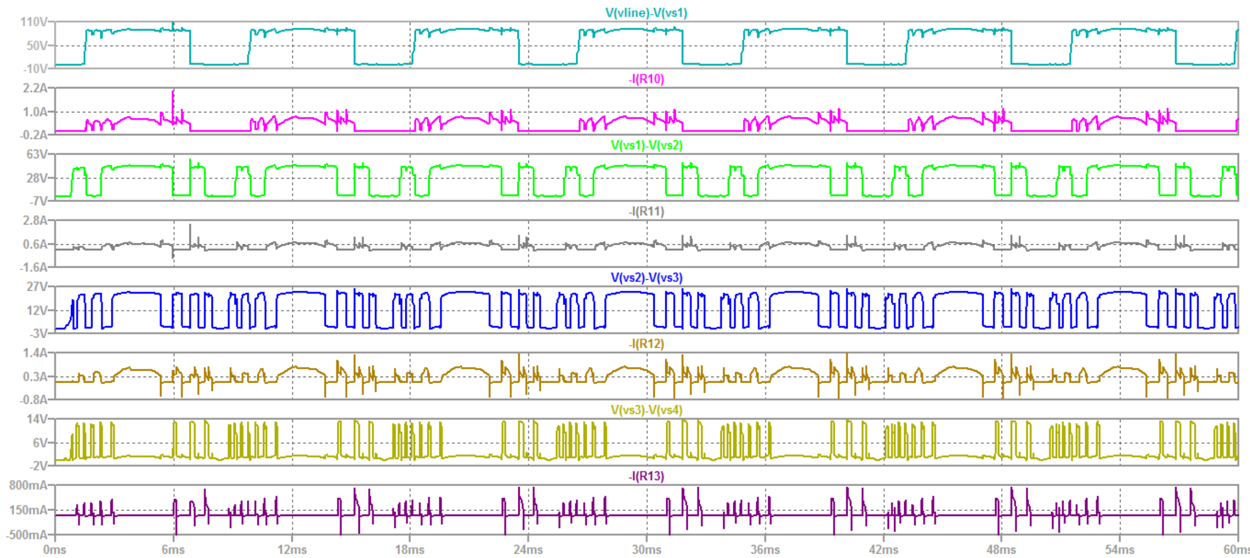

Figure 4-19: From top to bottom: stack one voltage, stack one current, stack two voltage, stack two current, stack three voltage, stack three current, stack four voltage, stack four current.

Figure 4-19 shows that the switching signals modeled after the TPS92411 functionality are implemented and control current flow as desired. Figure 4-20 shows that the increased number of switching states has reduced the voltage dropped across the MOSFET to 2.62V. Thus far, the MOSFET voltage drop has proven to be the cause of the dominant loss in the system, so reducing this will invariably improve the efficiency of the system overall.

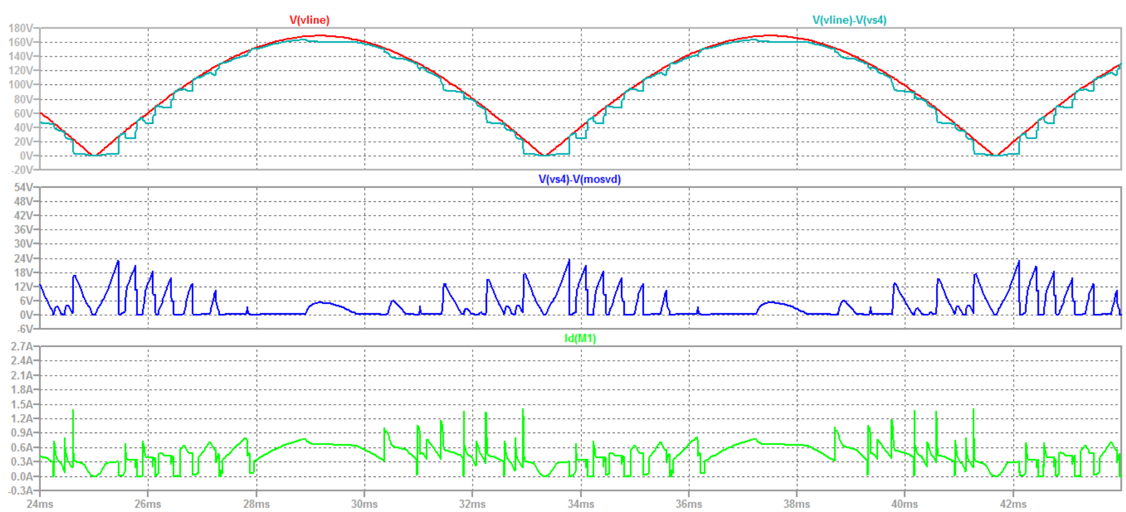

Figure 4-20: Rectified input voltage and total LED stack voltage, MOSFET drain-to-source voltage, MOSFET drain current.

The efficiency of this configuration, summarized in Table 4-7, is improved above the previous configurations due to the reduced MOSFET voltage, and by extension MOSFET loss. Overall efficiency is improved more than 15% over configuration 2 to 90.43%. The MOSFET loss is still dominant but is now closer to the loss on the current-setting resistor. This information is summarized visually in Figure 4-21.

Table 4-7: Summary of power distribution of configuration 3.

P_{in}	56.523W
P_{out}	51.115W
P_{MOS}	1.593W
P_{RS}	1.249W
P_{RECT}	0.811W
P_{SW}	0.871W
η	90.43%

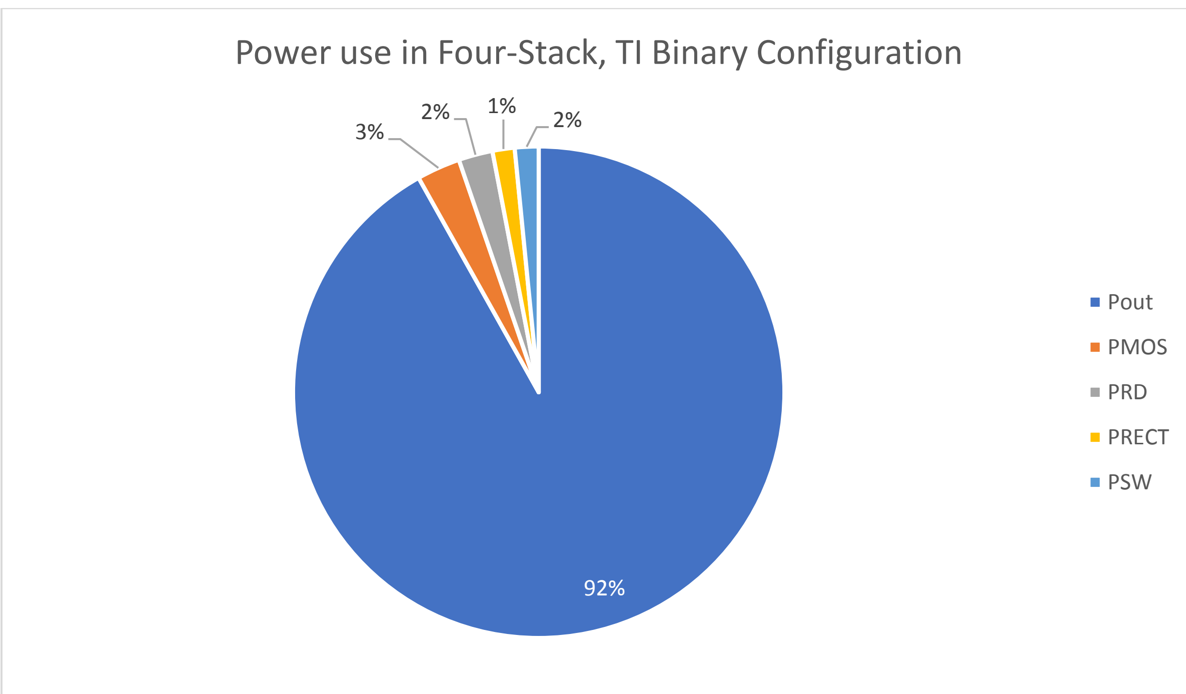

Figure 4-21: Power use as a percentage of input power.

Since this configuration had high enough efficiency to be viable, it was also tested with different rectifier diodes and switch resistance. This testing is summarized in Table 4-8. Ultimately, since the rectifier and switch losses represent smaller losses compared to the linear regulator losses, reducing them does little to help overall efficiency. Additionally, reducing voltage drop on the rectifier or switches simply increases the voltage on the MOSFET, increasing that loss. Components were selected that were the desired type but met the specifications of the original part [15].

Table 4-8: Comparison of component changes in configuration 3.

	Original	UPSC600 Schottky Rectifier	RF071L4S Fast-Recovery Rectifier	EPC EPC2036 Switches (73mΩ)
P_{in}	56.523W	55.820W	56.445W	56.890W
P_{out}	51.115W	50.392W	51.032W	51.607W
P_{MOS}	1.593W	1.411W	1.563W	2.298W
P_{RS}	1.249W	1.224W	1.247W	1.249W
P_{RECT}	0.811W	1.065W	0.851W	0.813W
P_{SW}	0.871W	0.857W	0.870W	0.032W
η	90.43%	90.28%	90.41%	90.71%

Configuration 4: Five-Stack, TI Binary-Based Custom Switching

This configuration adds a fifth stack of LEDs with the goal of further reducing the voltage dropped across the MOSFET. Since an additional stack would have a very low voltage, it can fill in more places where there is enough headroom to turn the stack on. By starting with the previous configuration's switch scheme, baseline efficiency is acceptable, and any changes should improve from there. The specifications of this configuration are shown in Table 4-9 and Figure 4-22.

Table 4-9: Summary of configuration 4.

Number of LED stacks	5
Switching style	Custom
Stack one size	83V, 26 LEDs
Stack two size	42V, 13 LEDs
Stack three size	23V, 7 LEDs
Stack four size	10V, 3 LEDs
Stack five size	7V, 2 LEDs
R_{source}	3.7Ω

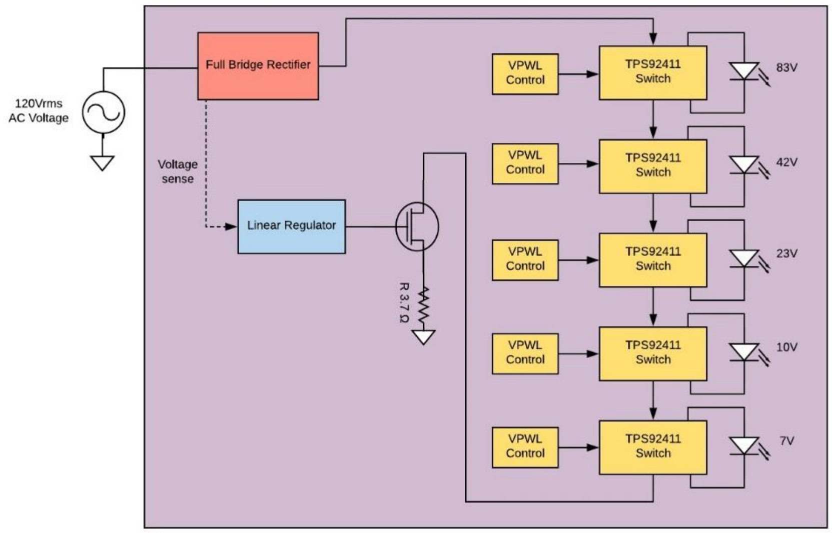

Figure 4-22: Block diagram description of configuration 4.

To begin the design of adding a fifth switch, the switch signal of the fourth stack was modified first. By assessing the MOSFET voltage waveform, time periods where there was enough headroom to activate the fourth switch were identified and added to the control file for switch four. Figure 4-23 demonstrates this process, with areas added in red. Once these additions were verified, the process was repeated with headroom of 7V, for a fifth stack with two LEDs. This stack was added in series with the rest, with the same type of voltage control. The switching signals are shown in Figure 4-24.

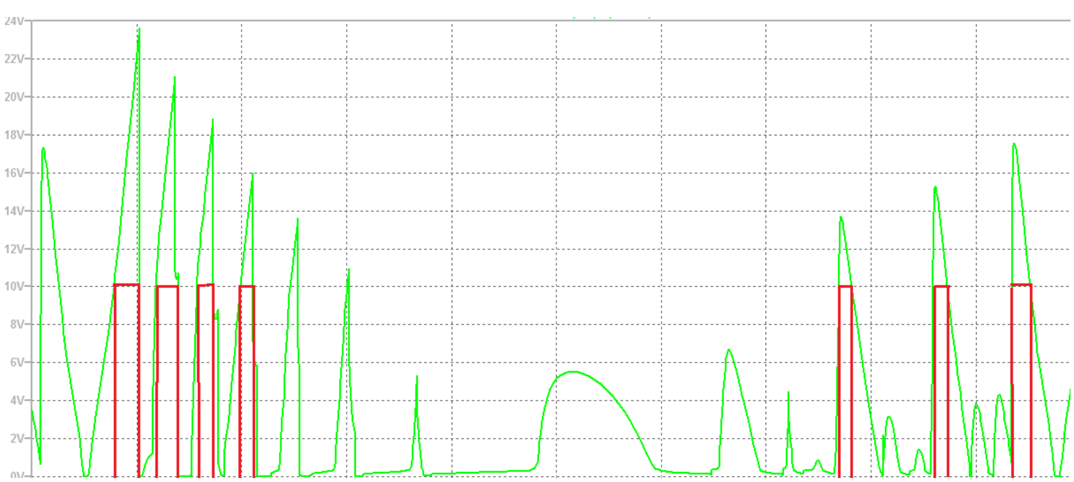

Figure 4-23: Example demonstrating where extra switch signals were added to improve beyond configuration 3.

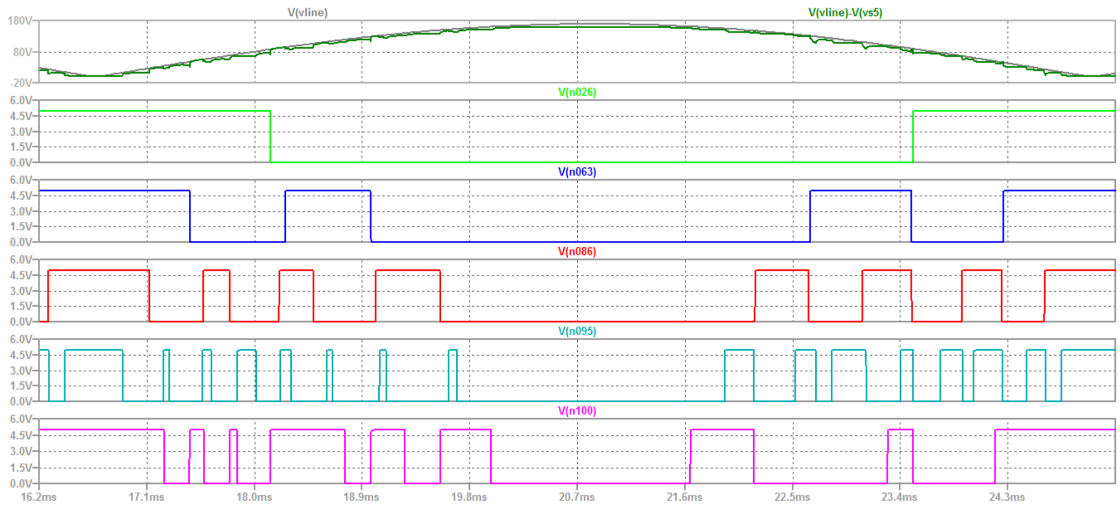

Figure 4-24: From top to bottom: Rectified input voltage and total stack voltage, switch signal one, switch signal two, switch signal three, switch signal four, switch signal five.

Figure 4-25 and Figure 4-26 show the new LED stack voltages and currents, respectively. The addition of the fifth stack required removing two LEDs from the largest stack and one LED from the second stack. This is reflected in the voltage of these stacks. These figures demonstrate the current set by the regulator is steered as designed.

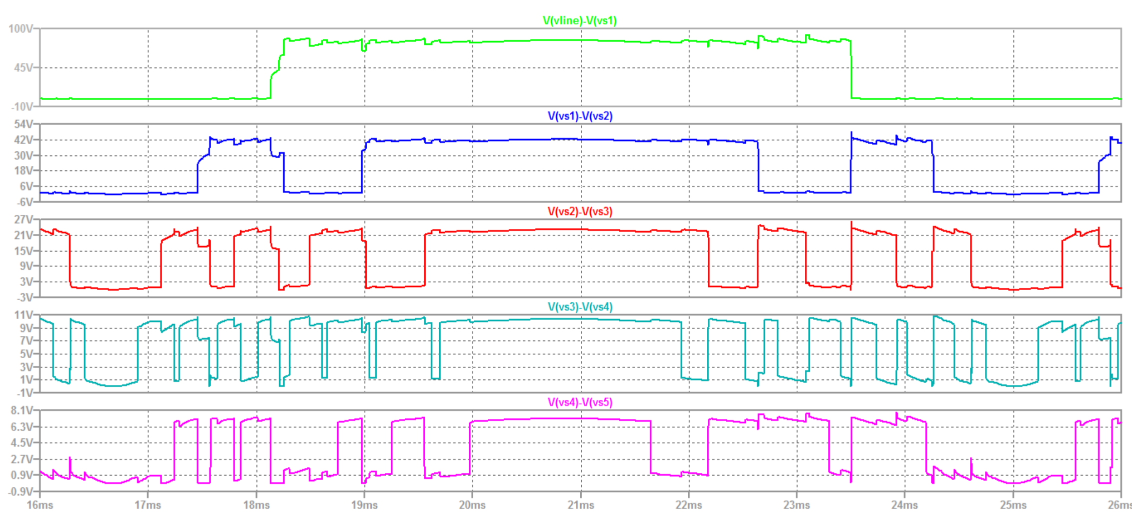

Figure 4-25: From top to bottom: voltage across stack one, two, three, four, five.

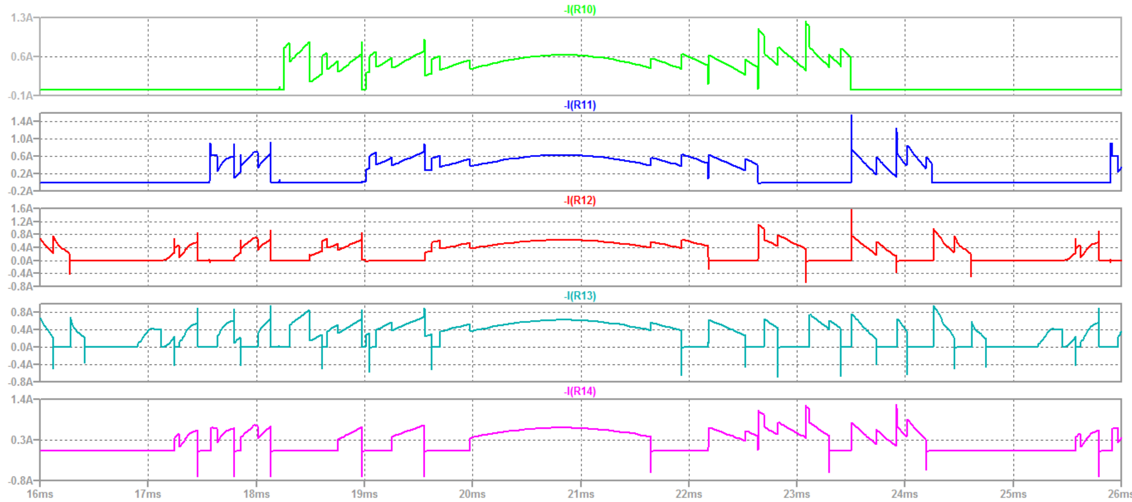

Figure 4-26: From top to bottom: current through stack one, two, three, four, five.

With the addition of the fifth switch, voltage across the MOSFET can be reduced significantly, as seen in Figure 4-27. In this case, the only times where there is greater than 1V across the MOSFET are during the very beginning and very end of the cycle of the rectified input voltage. This is when there is less than 7V in, and no stack can be activated. However, this reduces the average voltage across the MOSFET to 827mV. This is a significant improvement over an average of 31.6V across the MOSFET in configuration 1. The current shows the additional switching noise of another switch, but the overall current shape remains the same as previous iterations.

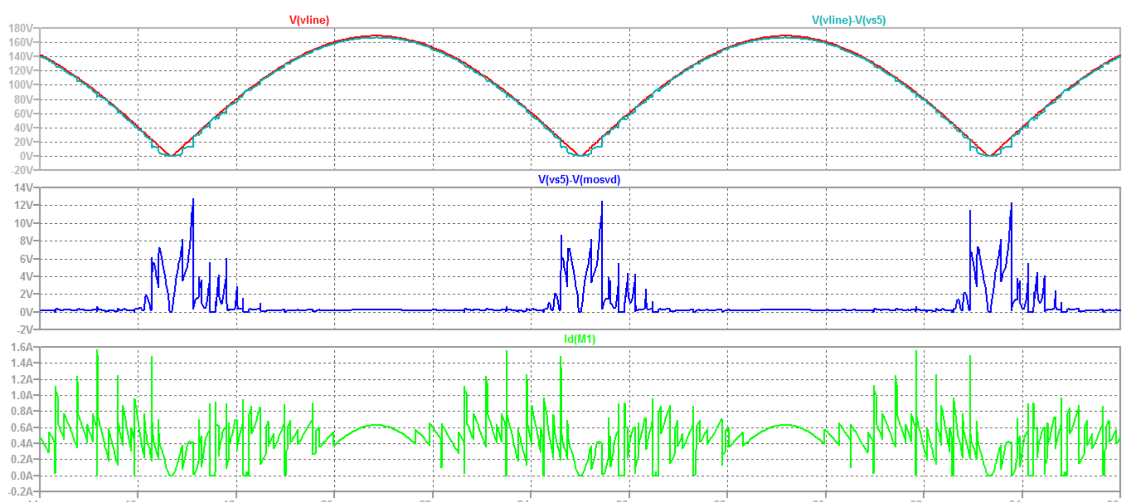

Figure 4-27: From top to bottom: Rectified input voltage and total LED stack voltage, MOSFET drain-to-source voltage, MOSFET drain current.

The input voltage and current (seen in Figure 4-28) are similar to the other configurations. The general shape of the current matches the shape of the input voltage, although the additional noise from switching reduces the power factor slightly to 0.905.

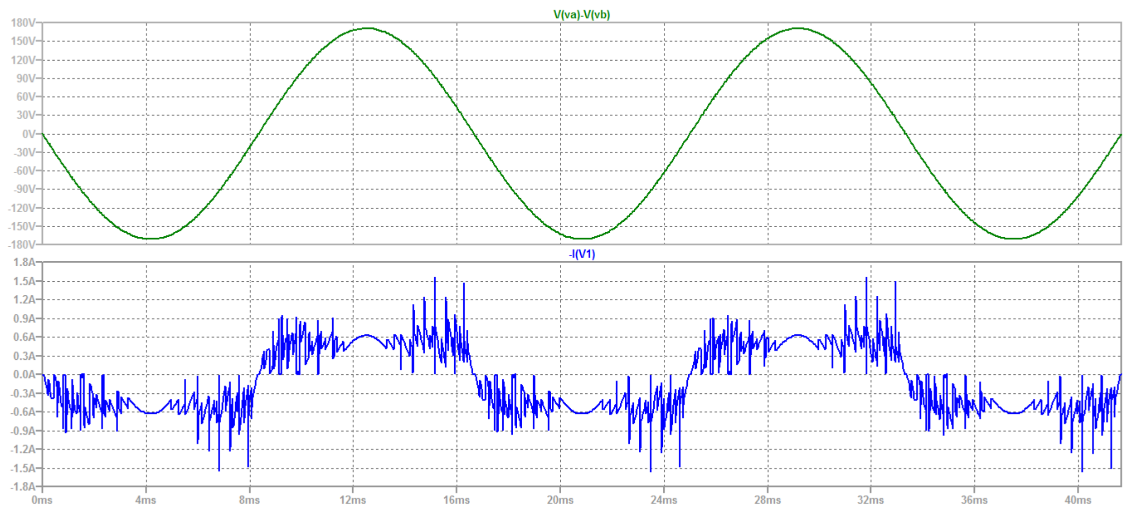

Figure 4-28: Input characteristic (voltage top, current bottom) of configuration 4.

The losses of this configuration are summarized in Table 4-10. Overall efficiency is improved approximately 2% from the previous version by adding an additional switch. This is mainly due to the reduced MOSFET loss, from 1.6W to 333mW. This is a 79% reduction in MOSFET loss from configuration 3. The rectifier and switch losses are relatively constant, as expected. Also, the addition of the extra stack of LEDs means that for the same output power, less current is needed in the system. This reduced the P_{RS} loss to under 1W. Figure 4-29 shows a visual representation of the use of input power in the system.

Table 4-10: Summary of power use in configuration 4.

P_{in}	55.546W
P_{out}	51.163W
P_{MOS}	**0.333W**
P_{RS}	0.966W
P_{RECT}	0.851W
P_{SW}	0.893W
η	92.10%

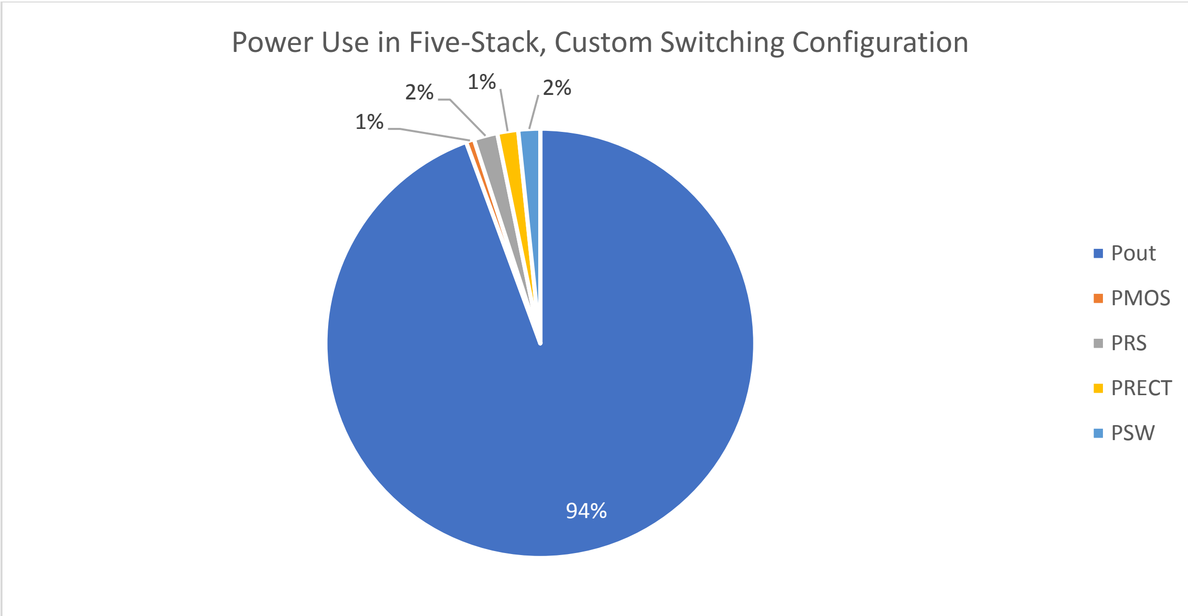

Figure 4-29: Power use as a percentage of input power.

Further Configurations: Why not more switches?

The data for each system, summarized together in Table 4-11, shows a trend that having more switches reduces loss in the system. Why not keep adding more? Unfortunately, without radically modifying the size of the LED stacks or concept of switching schemes, five switches is likely the limit for a practical system.

Table 4-11: Summary of power use in all configurations.

	Configuration 1	Configuration 2	Configuration 4	Configuration 5
P_{in}	78.984W	69.346W	56.523W	55.546W
P_{out}	51.536W	51.140W	51.115W	51.163W
P_{MOS}	22.362W	13.551W	1.593W	0.333W
P_{RS}	1.734W	1.490W	1.249W	0.966W
P_{RECT}	1.176W	1.018W	0.811W	0.851W
P_{SW}	1.303W	0.818W	0.871W	0.893W
η	65.24%	73.75%	90.43%	92.10%

First, with a fifth stack of two LEDs, only one more stack could be added, with a single LED. Since a white LED has a drop of 3-3.5V or more at this size current, there is no way to turn on LEDs any sooner than when the input reaches 3.5V. Figure 4-27 shows that the only significant voltage drop on the MOSFET is during the very beginning and end of the cycle. Having a 3.5V stack could only help a small amount with this. Additionally, the sections of the waveform that would allow a 3.5V stack to be on are so short, that it would likely be impractical to implement in a physical system.

Finally, with five switches, the MOSFET loss is no longer dominant. To improve efficiency, other aspects of the system need to be altered. As seen in configuration 3, improving the switches or diodes in the rectifier only increased the voltage on the MOSFET, increasing this loss once again. The new dominant loss is the current-limiting resistor, but the loss on that resistor is set by the output power. A 50W system creates a restraint on the current through the resistor, and the resistance value sets this current, so there is an I^2R loss that is unavoidable and unchangeable. The linear regulator in this circuit is a simple and necessary solution to regulate current and drop extra voltage, but the tradeoff is a power loss. The fundamental design of this system requires it, so the loss must simply be minimized. Furthermore, if the linear regulator were represented as a black box, with any kind of regulator inside, the losses would be the same because the current into the box is determined by the output power and the voltage across it is determined by the switching signals (voltage dropped on the LEDs). This means that more creative solutions or fundamental changes must be made to the system to improve efficiency further.

Chapter 5 : Conclusion

The goal of this project was to investigate, through simulation, the highest-loss parts of a typical AC LED direct drive system so that future versions of the system could benefit from increased efficiency. Starting with a TI reference design, this project demonstrates common methods of AC driving LEDs, as well as versions not used yet in practice to illustrate the dominant losses of the system and ways in which they can be reduced.

Four main configurations were simulated and measured: a three-stack binary switching system, a four-stack step-up switching system, a four-stack binary switching system, and a five-stack binary switching system. Through each simulation, the common theme was that the loss of the linear regulator was the dominant loss of the system. This consisted of loss on the MOSFET and the current-setting resistor.

Since the voltage drop across an LED is relatively constant for a given current, the current through the system determines the output power. This means the resistor loss is relatively unalterable since the resistance sets the current in the system and the current is determined by output power rating. The only variable that can reduce linear regulator loss is the voltage across the MOSFET. Any voltage not dropped across LED stacks at any given time is dropped on the MOSFET. This set of simulations found that increasing the number of switches, with a switching scheme based around minimizing MOSFET voltage, was the best way to increase efficiency of the system. With three stacks using binary switching, MOSFET loss was 22.4W, or 29% of input power. With five switches, the MOSFET loss was reduced to 333mW, or less than 1% of input power.

The other main losses in the system measured were from the input rectifier and switches. Increasing the number of LED stacks reduced both losses, due to less current in the system needed for the same output power. Different types of rectifier diodes (pn, fast recovery, Schottky) were added to the simulation of configuration 4 (the TI design) to see if efficiency improved. These improved diodes did reduce loss on the input rectifier, but the reduced voltage drop across them increased the voltage drop on the MOSFET, rendering overall efficiency nearly the same. The component change that yielded the highest efficiency gain was the switches. The TPS92410 has an internal 2Ω MOSFET, so this value was used for all other simulations. With a MOSFET having smaller R_{DSon} of 17mΩ, the switch loss was reduced to 32mW. However, this change increased MOSFET loss by over 1W, and only increased overall efficiency 0.30%. So, it appears the MOSFET loss is the most important part of the system to monitor to reduce loss and improve efficiency.

Even though this simulation shows increasing the number of switches in an AC LED system increases efficiency, this is not the only, or necessarily optimal, set of switch signals for this system. The goal was to investigate sources of loss and demonstrate ways to reduce these losses. Therefore, we see that adding more switches increases efficiency, but there are many possible variations of LED stack sizes and switch signal timing that may provide similar or improved results. There are more combinations possible than could be covered here, so this area would be beneficial to study in the future. Additionally, research into how these findings vary with the power rating of the system would be useful to know. The dominant losses and methods for improvement may hold true at a wide range of power levels (from a small 10-15W lightbulb, to a 200W stadium light), or may be varied with output power. Another area of future research could be building the final system simulated here in hardware, to verify the improved efficiency calculated.

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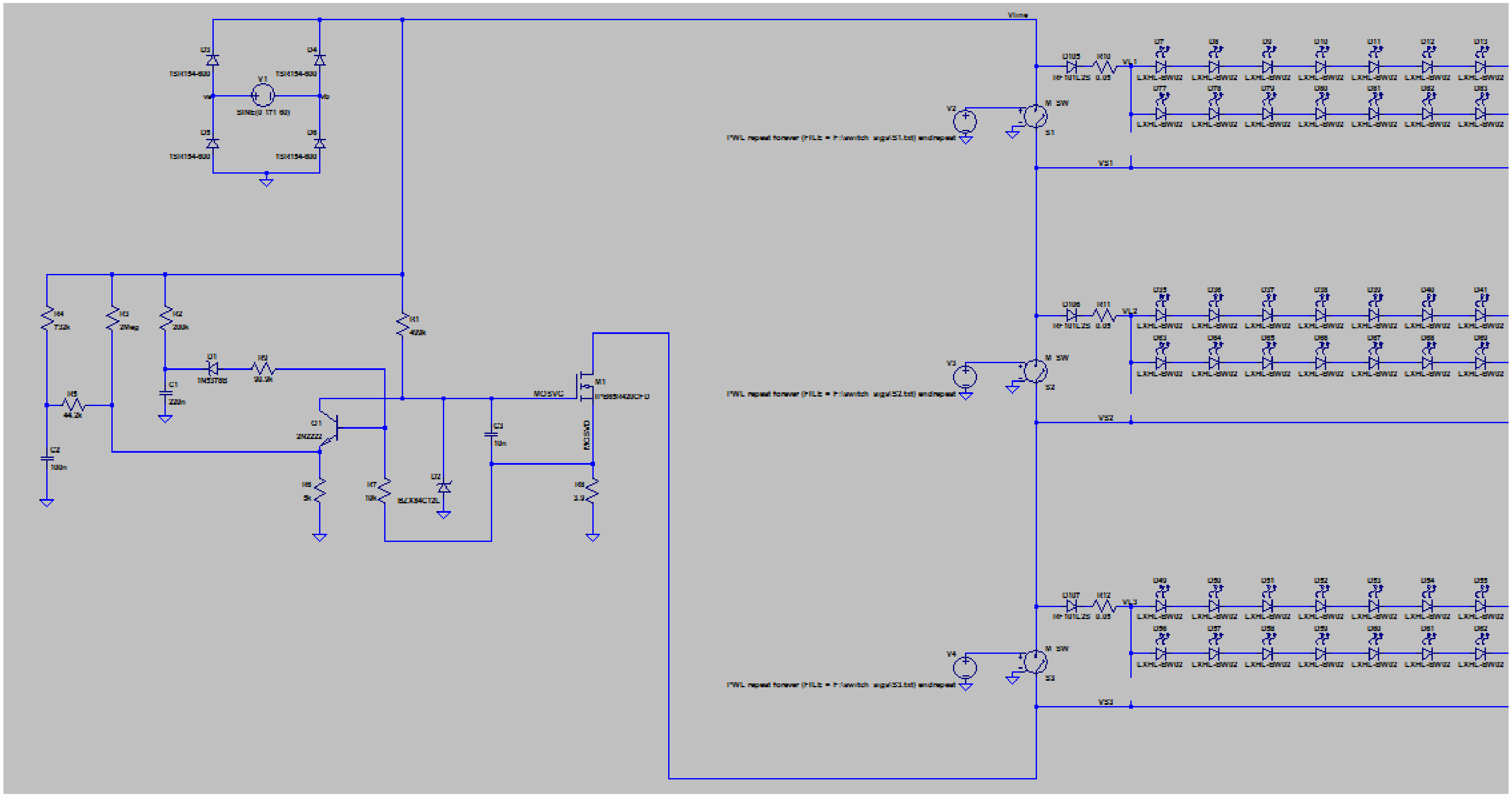
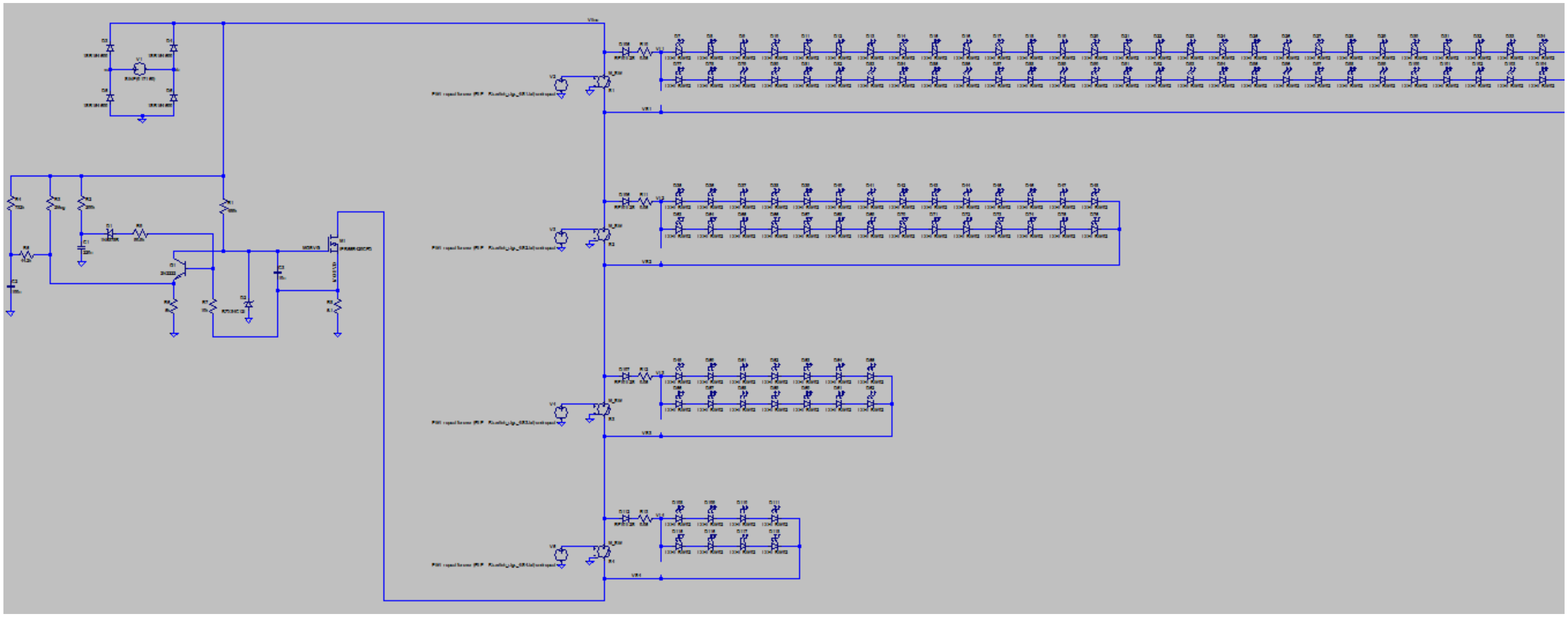
Appendix

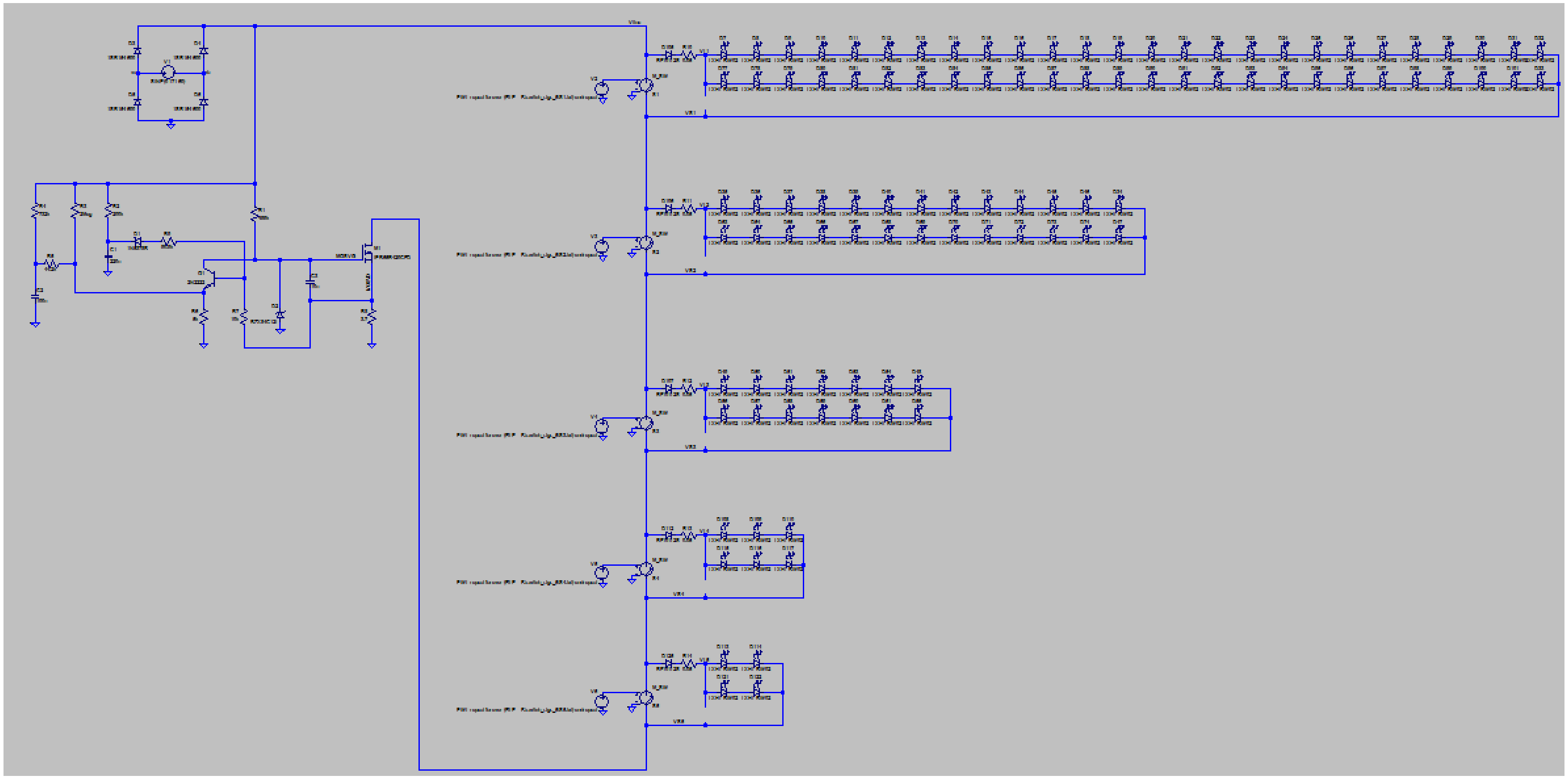
Configuration 1: Schematic



Configuration 2 and 3: Schematic



Configuration 4: Schematic



Analysis of Senior Project Design

Project title: Investigating Efficiency of AC Direct Drive of LED Lighting

Student name: ______________________ Student signature: ____________________________

Advisor name: ______________________ Advisor initial: _________ Date: _______________

Summary of functional requirements:

The goal of this project is to develop a flexible simulation of a generic AC LED system to identify and attempt to improve areas of significant power loss. The findings from this project can be used when designing new iterations of AC LED systems to improve system performance and increase system efficiency. This simulation should represent a common AC LED system as a baseline, with options to modify major components (LEDs, rectifier diodes, switches, linear regulator), as well as switch signal timing. The simulation can be used to analyze results of circuit changes by measuring important voltages and currents, as well as power provided by the source and lost on different components.

Primary Constraints:

Constructing an intuitive, flexible, and fast simulation of a relatively large system was the main difficulty in this project. Initially, a PSPICE model of the TPS92410 was to be used in Cadence. This did not function as desired at a power level of 50W, due to constraints inherent in the model. TINA TI can run simulations with the IC models, but measuring data proved difficult and the simulation took over half an hour to run. Eventually, the goal became to create the most generic AC LED system possible, where LED stack size, switch signals, and number of switches could all be easily modified and analyzed. This proved to be the best option, since adding LED stacks and modifying switch signals created the most efficient design.

Economic:

As of now, LED bulbs are more expensive and less commonly used than fluorescent or CFL bulbs [6]. However, CFL blubs are reaching their limits of efficiency. To continue to improve lighting efficiency, LED bulbs could be used. To encourage their use, prices need to come down and are projected to do so [7]. AC LED systems offer a less expensive option, due to the lack of large magnetics and semiconductor-based approach. A cheaper, more efficient system means lighting that is less expensive to install, as well as less expensive to power over its life. AC driving's other advantage is that the lifespan of the driver better matches the lifespan of the LEDs, so lighting would need to be replaced less often, reducing waste and saving money. This could save money for large companies in office buildings, sport stadiums, large parking lots, and any other company or entity requiring large-scale lighting.

If Commercially Manufactured:

Since this project uses a generic version of the main current-steering switches and control, it is difficult to estimate the cost of a final product. These components would likely be two of the most expensive and the two most likely to change based on approach. LED bulbs in general cost an average of $7.53 in 2015 and are projected to come down to $2.00 by 2040 [8]. With a projected lifespan in 2040 of 50,000 hours, they will need to be replaced far less often as well. Increased efficiency from 93 to 160 lumens per watt will reduce maintenance costs as well.

Manufacturability:

Manufacture of semiconductor devices has gotten easier and cheaper as time has gone on, but this system has some manufacturing concerns. For one, with over one hundred LEDs in the final system, PCB layout and enclosure consideration becomes potentially difficult. Tradeoffs between a compact design and heat dissipation will come into play. The linear regulator in the system will likely require a heatsink, and this will have impacts on enclosure design and shape.

Environmental:

As a finished product, this lighting solution would be more efficient than other options, and therefore use less energy. Since most energy in the United States comes from non-renewable sources, using these resources effectively is important [2]. Once in use, this lighting solution should use less energy and las longer than comparable DC-DC based systems because of the lack of large input filtering capacitors. A longer lifespan means less electronic waste since they are discarded less often. This solution has many semiconductor devices, with over one hundred LEDs, five MOSFET switches, four input rectifier diodes, a power MOSFET, multiple linear regulator transistors, and more. Manufacture of semiconductors is harmful for the environment, requiring large quantities of water and energy. The goal would be to have the efficiency and long life outweigh the harmful production of the devices.

Sustainability:

Since the goal of this project is to improve efficiency of a lighting design, it is eventually contributing to the sustainability of energy use. One aspect of this project that does not improve sustainability is increasing the amount of semiconductor devices needed in the lighting system. With a goal of more switches, LEDs, and control ICs, a light made this way has more semiconductors than a fluorescent or incandescent bulb. The semiconductor industry is known for using a large amount of water and other natural resources to be produced. Hopefully, the efficiency increases from the design of the system can offset this energy and resource use. Additionally, one of the main reasons to use AC LED driving is to better match the lifespan of the driving hardware to the life of an LED device. As discussed earlier, an LED can have a lifetime of 50,000 hours, but a large electrolytic capacitor on the input of a DC-DC converter has a lifespan of 15,000 hours. Combining the lower cost of manufactured semiconductors, higher efficiency of this system, and longer lifetime of AC LED systems in general, will create a sustainable lighting product.

Health and Safety:

LED light bulbs pose some safety concerns, due to the inherent flicker of the light. In an AC LED system, LEDs are turning on and off quickly, while the overall brightness of the set raises and lowers in intensity at 120Hz (rectified line frequency). Flicker in fluorescent bulbs is known to cause headaches in some individuals, and although there is less data for LED bulbs, it is suspected the same would occur [16]. This simulation does not address flicker since the goal was maximizing efficiency. However, if this were to be made into a commercial product, research would have to be done into the effects of flicker and the circuit must be modified for safe use, even at the expense of efficiency.

Ethical:

As the health and safety section discussed, flicker in lighting can cause headaches and other adverse effects when people are subjected to them for long periods. In most cases, flicker reduction and efficiency increase are opposed to one another, so ethically this tradeoff must be negotiated to create a safe product for human use. This could include modifying the circuit to reduce flicker at the expense of efficiency or using the product only in places where flicker is less important, such as for gas station downlights. These would be areas where light is necessary, but it need not be as high quality as in a workspace.

Social and Political:

Some of the main benefits of AC LED driving are that the system is simpler and does not require bulky, expensive magnetics. This reduction in cost and complexity could mean that more efficient, cheaper lighting alternatives are more readily available. Reduced cost means a lower barrier to entry for those with less money, and the higher efficiency means lower cost throughout the life of the system. Also, if more energy efficient options are available to more people, we can reduce energy use on a grand scale. Smaller power lighting solutions would be useful in homes, while high-power devices could help with public parks or children's sports facilities. This accessibility is important to promote equality and energy efficiency.

Development:

This project was an education in simulation and because multiple programs were used initially, this project demonstrated key differences and similarities between programs. For example, OrCAD PSPICE Lite is useful for small simulations of standard or generic components, but the limitations on circuit size made it impossible to use any manufacturer-provided model. All the programs used (OrCAD PSPICE, Cadence, TINA, and LTSPICE) operate off of a common backbone of SPICE simulation and offer similar simulation options. The major differences between them are availability and usability. LTSPICE, OrCAD, and TINA are free and downloadable. These readily available programs do much of what a user would need. Cadence is a very exclusive and expensive license. This is because of the large libraries of components available, as well as PCB and other software. Ultimately, for this project the humble LTSPICE proved to be the most usable, with easy modification of a generic circuit and accurate models of semiconductor components.