DC-DC Buck Boost Converter using the LT8390 Controller and GaN High Electron Mobility Transistors

by

Brian Keokot
Juan Urbano

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT
California Polytechnic State University
San Luis Obispo

June 04, 2021

Table of Contents

List of Tables

List of Figures

List of Abbreviations

EHFEM: Energy Harvesting from Exercise Machines

Abstract

California Polytechnic State University, San Luis Obispo's ongoing Energy Harvesting from Exercise Machines (EHFEM) project creates a sustainable energy source by converting physical exercise from exercise machines into renewable electricity. Implementing energy harvesting technology into the Recreation Center's exercise machines helps Cal Poly make progress on its goal of carbon neutrality by 2050 [1]. An improvement to the system with new technology increases Cal Poly Recreation Center's ability to save money and improve sustainability.

The focus of this project improves the design of Nicholas Serres, who used the LT8390 controller in his buck boost DC-DC converter [2]. This project improves the efficiency of the EHFEM system by utilizing GaN HEMTs instead of MOSFETs and lowering the power dissipation within the transistors. The converter aims to lower the utility bill of the Cal Poly Recreation Center.

Chapter 1: Introduction

As the human population increases, resources deplete at an alarming rate, and the danger of global warming rises [3]. With climate change becoming the largest problem facing the next generations, slow cultural shifts must occur to prevent climate disasters from taking place. The best strategy involves incentivizing eco-friendly behavior by creating/implementing cost-effective practices. One of the ways to create a cultural shift involves the Energy Harvesting from Exercise Machines (EHFEM) project at Cal Poly.

Since 2007, Dr. Braun has advised multiple teams to work on EHFEM projects. EHFEM aims to provide renewable energy back to the power grid by harvesting energy from the Cal Poly Recreation Center's elliptical machines. This project is an addition to the many different Four-Switch Buck-Boost DC-DC converters available to use [4]. Alvin Hilario, a student that worked on an EHFEM project, determined that a four-switch DC-DC converter works best with the EFHEM system [5]. This project design uses an LT8390 Four-Switch Buck-Boost converter, adding to the pool of DC-DC converters generated through Cal Poly senior projects. Previous converters include *Energy Harvesting From Exercise Machines: Buck-Boost Converter Design by* Andrew Forster [6] and *DC-DC Converter for Harvesting Energy from an Exercise Bike by* Henry Ureh and Chris Henry [7], all former students of Cal Poly that worked on an EHFEM project.

The converter builds upon past EHFEM projects. EHFEM requires exercise machines, input and output protection systems, a DC-DC converter, and an inverter to connect the power to the electrical grid. This project focuses on the DC-DC converter aspect of the whole system. An input protection system added by Turner and Weiler [8] and Chu and Yoo [9] and an inverter from Enphase [10] complete the system. The newly designed DC-DC converter seeks to improve upon the past design iterations provided by Wong who used an LT3791 controller [11] and Burk, Bhula, McKay, Matteo [12-13] who used the LT8705 controller in their DC-DC converters. The next section goes over the following requirements and specifications for the LT8390 controller.

Chapter 2: Customer Needs, Requirements, and Specifications

The following chapter explains the project's specifications and assesses the customer's needs.

Customer Needs Assessment

The customers of this project include the Cal Poly Recreation Center and other gym owners. The Cal Poly Recreation Center requires the DC-DC Buck Boost Converter to efficiently convert energy and allow affordable mass production. The product must pay for itself within ten years after purchasing and begin generating revenue for the customer. Cost plays a major role not only in material cost but also in overall cost to the Recreation Center. For Cal Poly's Recreation Center to purchase the product, it needs to pay for itself over ten years [5]. Higher levels of system efficiency means converting the user's energy to output power for speeding up the process of repaying the cost of the system. Size of the system also plays a major role, because it must not change the functionality of the machine and risk discouraging participants from using it. The customer needs given by previous EHFEM projects help build the current customer needs. This sustainable system must be cost effective and be efficient in power usage. These customer needs build the requirements and specifications of the project, as the project must tailor to the customer needs.

Requirements and Specifications

The EHFEM system addresses environmental concerns by converting the exercise machine user's energy to grid power. To address these concerns, the DC-DC Buck Boost converter must demonstrate higher efficiency than the previous iterations [7]. The customers require a profitable and affordable project. The system must meet safety standards for commercial use, and its size must not alter the exercise machine's functionality. Without these requirements, Cal Poly's Recreation Center would not consider purchasing the final product.

The marketing requirements determine the specifications to fulfill the project's goal. Specifications, such as size and cost restrictions, come from the customer's profitability goals and needs [13]. The project must not hinder the user's experience and does not stand out or become a safety hazard. Meeting safety guidelines and ensuring compliance with all laws the design must follow the rules employed by the NEC, UL, RoHS, and IEEE 1547 standards [7].

Previous EHFEM projects use an elliptical machine to harvest the energy from the user. The DC-DC converter receives this energy from the user and then delivers the power to a microinverter. Since the microinverter derives from a previous EHFEM project, the LT8390 must operate successfully with the system [10].

Table I displays all the project's specifications generated from the customer's profitability goals and needs.

TABLE I: DC-DC BUCK BOOST CONVERTER REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements	Engineering Specifications	Justification
1, 5, 6	The converter meets a minimum 95% efficiency average output power rating.	Maximum average power output efficiency shows a peak at 98% [14]. 95% balances between high efficiency and low cost.
5, 6	The converter receives an input between 6-60 VDC.	LT8390 datasheet [14] indicates a range of 4-60 V. To meet the efficiency requirement, the input ranges from 6-35 V.
5, 6	The converter outputs 36 VDC ± 1 VDC.	The inverter [7] indicates a peak efficiency at an output voltage of 36 V.
2, 3, 4	The converter fits within a 6"x 6"x 2" package.	Design must fit inside the exercise machine.
1	Material costs do not exceed $250.	The project must save the customer money.
4, 5, 6	The DC-DC converter output current does not exceed 10 A.	An elliptical machine's current output reaches up to 6 A. Efficiency constraints need at most a 10 A output [14].
3, 4	Temperature of DC-DC converter components does not exceed 120 °F.	Temperature can potentially damage the machine or user. Exercising at gyms increases the overall room temperature so temperature of the system must account for outside temperature.
4	System meets NEC, UL, RoHs, and IEEE 1547 standards.	Must meet standards for safe electrical and mechanical operations.
1, 3, 6	Connectors use spade lugs inputs to connect to the elliptical and banana plugs output to connect to the converter.	Familiar connectors allow quick and easy installation.
2, 3	The converter fits within a dark colored enclosure in the elliptical machine.	Does not interfere with the machine's usage or aesthetic. Most exercise machines are dark in color.

2, 3, 4	Enclosure fits within the already existing shell of the elliptical machine.	A separate enclosure would crowd the Recreation Center and may interfere with the machine's usage.

Marketing Requirements
1. Low cost
2. Reasonable size
3. Does not interfere with machine's usage
4. Safe to use
5. Efficient design
6. Sustainable

Table II below contains a summary of the most important deadlines of the project. It includes the design review, two demos, two reports, and the creation of the Senior Project Expo poster.

TABLE II: DC-DC BUCK BOOST CONVERTER DELIVERABLES

Delivery Date	Deliverable Description
2/19/21	Design Review
3/12/21	EE 461 demo
3/19/21	EE 461 report
5/17/21	EE 462 demo
5/18/21	ABET Sr. Project Analysis
5/19/21	Sr. Project Expo Poster
6/7/21	EE 462 Report

The next section refers to the functional decomposition of the project system. The system and requirements clarifies the needs of the project, and the next section breaks down how the project works with other systems.

Chapter 3: Functional Decomposition

Chapter 3 explains the low-level block diagram of level 0 and level 1, along with a function table describing the diagram. Each section goes into detail on what the block diagram illustrates.

Level 0 Block Diagram and Function Table

Figure 1 below shows the project's Level 0 block diagram. It contains the inputs and outputs of the DC-DC Buck Boost Converter at its simplest form. Table III explains *Figure 1* in further detail. It provides information such as the controller used and the functionality of the project. The Level 1 Block Diagram goes into further detail of how the project works.

6 - 60 VDC → **DC-DC Buck-Boost Converter** → 36 ± 1 VDC

0 - 6 A   0 - 10 A

Figure 1: **Level 0 Block Diagram of DC-DC Buck Boost Converter**

TABLE III: DC-DC BUCK BOOST CONVERTER LEVEL 0 INPUTS, OUTPUTS, AND FUNCTIONALITY

Module	DC-DC Converter using LT8390 Controller
Inputs	Input voltage ranging from 6 V to 60 V Input current ranging from 0 A to 6 A
Outputs	Output voltage of 36 V ± 1 V Output current ranging from 0 A to 10 A
Functionality	Converts input voltage from the exercise machine to an output voltage for the inverter.

Level 1 Block Diagram and Function Table

Figure 2 below shows the project's Level 1 block diagram. It contains the inputs and outputs of the DC-DC Buck Boost Converter with the LT8390 controller. Table IV-VII explains *Figure 2* in further detail. It provides information such as the controller pins used and the functionality of the R_{Sense} resistor.
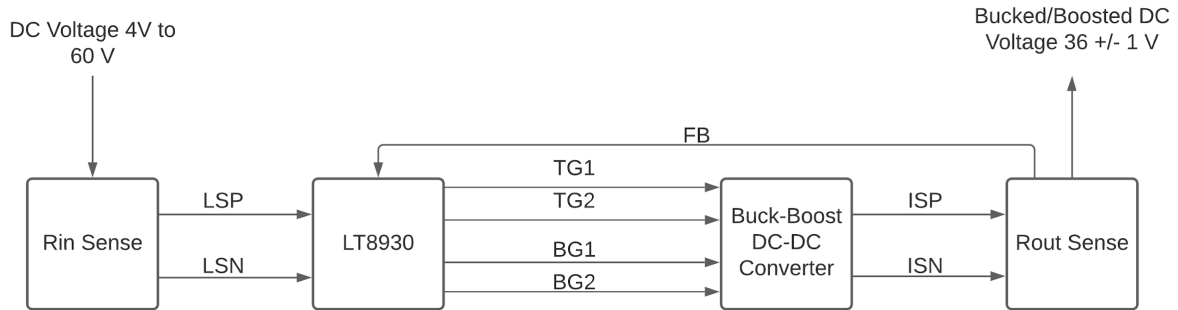
***Figure 2:* Level 1 Block Diagram of DC-DC Buck Boost Converter**

TABLE IV: R_{IN} SENSE FUNCTION TABLE

Module	R_{IN} Sense Resistor
Inputs	● Input voltage ranging from 4 V to 60 V DC
Outputs	● LSP: Positive input of Buck Side Inductor Current Sense Resistor ● LSN: Negative input of Buck Side Inductor Current Sense Resistor
Functionality	Ensures accurate current sense with Kelvin connection. Minimizes power consumption of the circuit.

TABLE V: LT8390 FUNCTION TABLE

Module	LT8390 Controller
Inputs	● LSP: Positive input of Buck Side Inductor Current Sense Resistor ● LSN: Negative input of Buck Side Inductor Current Sense Resistor ● FB: Feedback pin, used for constant voltage regulation and output fault protection
Outputs	● TG1: Controls the Buck Side MOSFET, turns on or off ● TG2: Controls the Boost Side MOSFET, turns on or off ● BG1: Controls the Buck Side MOSFET, turns on or off ● BG2: Controls the Boost Side MOSFET, turns on or off
Functionality	The gate voltages (TG1, TG2, BG1, BG2) control the MOSFETs which act as switches. In controlling these switches the gate voltages determine how the converter behaves: buck, boost, and buck-boost.

TABLE VI: BUCK-BOOST DC-DC CONVERTER FUNCTION TABLE

Module	Buck-Boost DC-DC Converter
Inputs	● TG1: Controls the Buck Side MOSFET, turns on or off ● TG2: Controls the Boost Side MOSFET, turns on or off ● BG1: Controls the Buck Side MOSFET, turns on or off ● BG2: Controls the Boost Side MOSFET, turns on or off
Outputs	● ISP: Positive input of Boost Side Inductor Current Sense Resistor ● ISN: Negative input of Boost Side Inductor Current Sense Resistor
Functionality	DC-DC converter operates in: buck, boost, or buck-boost mode depending on the previous gate voltages (TG1, TG2, BG1, BG2) of the LT8390 controller. Connects to R_{OUT} Sense resistor for voltage regulation and output fault protection.

TABLE VII: R_{OUT} SENSE FUNCTION TABLE

Module	R_{OUT} Sense Resistor
Inputs	● ISP: Positive input of Boost Side Inductor Current Sense Resistor ● ISN: Negative input of Boost Side Inductor Current Sense Resistor
Outputs	● FB: Feedback pin, used for constant voltage regulation and output fault protection ● Bucked/Boosted 36 V ± 1 V DC
Functionality	Provides accurate current sense with Kelvin connection. Minimizes power consumption of the circuit. Provides feedback via FB pin for voltage regulation and output fault protection.

In the next chapter, the project planning shows how the team members must cooperate to create the project within the time frame. The cost estimates of parts and labor show the potential cost required to build the project and fund it.

Chapter 4: Project Planning

The cost estimate lists the parts' price and amount needed for the project. The section labeled *Actual Costs* goes over the final, actual costs of the project. The Gantt Chart documents the planning, designing, and simulating phases of the project. The next section goes over the cost estimates of the project.

Cost Estimates

Table VIII presents a list of parts we expect to use while developing the DC-DC buck-boost converter using the LT8390 controller. It contains resistors and capacitors of varying values. MOSFETs, heatsinks, and the controller are also included. Table VIII splits the cost by cost per unit and total costs. The components included in this table receive influence from the component lists from previous iterations of the DC-DC converter such as Wong [11] and Matteo [2].

TABLE VIII: DC-DC BUCK BOOST CONVERTER ESTIMATED PARTS LIST

COMPONENT PARTS	VALUES	# OF COMPONENTS	COSTS PER UNIT	TOTAL COSTS
RESISTORS	1.5 M	2	$0.10	$0.20
	510 K	4	$0.50	$2.00
	500 K	2	$3.00	$6.00
	200 K	4	$0.76	$3.04
	50 K	2	$2.77	$5.54
	27 K	2	$1.94	$3.88
MOSFETS	TO-247	8	$4.31	$17.04
CAPACITORS	4.7 MICRO	10	$0.50	$5.00
	1 MICRO	2	$0.38	$0.76
	0.1 MICRO	4	$0.24	$0.96
	22 NF	2	$0.36	$0.72
HEATSINK	TO-247 HEATSINK	8	$2.13	$17.04
PCB		3	$30.00	$90.00
LT8390		5	$5.65	$28.25
FINAL COSTS				$180.43

Table IX contains the calculated labor costs of the project. A senior project at California Polytechnic State University, San Luis Obispo expects to take around 420 hours to complete. A simple Google search yields that an average electrical engineer hourly wages in California approximates to $63, but we lowered it to $56.25 for entry level positions. The most optimistic time to complete the project approximates to 360 hours, and the worst possible completion time approximates to 500 hours. The average estimated time approximates to 420 hours. Using equation 6 located in chapter 10 of Ford & Coulston [13] the total became $23,813 per team member. The next section goes over the Gantt chart documentation of the project.

TABLE IX: DC-DC BUCK BOOST CONVERTER LABOR COSTS

LABOR	LABOR COSTS AMOUNT
OPTIMISTIC TIME	360 HOURS
ACTUAL ESTIMATED TIME	420 HOURS
PESSIMISTIC TIME	500 HOURS
APPROXIMATE ENTRY LEVEL SALARY	$56.25/HR
TOTAL LABOR COST	$23,813 PER TEAM MEMBER

Actual Costs

With the ongoing pandemic and the shortage of many electronic parts, the team with the guidance of our advisor decided that we would not build our project but instead focus on simulating and doing the PCB design using the parts in Table X.

TABLE X: DC-DC BUCK BOOST CONVERTER FINAL PARTS LIST

COMPONENT PARTS	VALUES	# OF COMPONENTS	COSTS PER UNIT	TOTAL COSTS
RESISTORS	309 K	1	$0.02	$0.02
	300 K	1	$0.10	$0.10
	120 K	1	$0.02	$0.02
	100 K	2	$0.10	$0.20
	75 K	1	$0.28	$0.28
	60 K	1	$5.98	$5.98
	27 K	1	$0.14	$0.14
	5 K	1	$0.15	$0.15

	3 K	1	$0.17	$0.17
	4 MILI	1	$0.73	$0.73
	3 MILI	1	$0.71	$0.71
CAPACITORS	5 MICRO	1	$6.66	$6.66
	4.7 MICRO	3	$0.48	$1.44
	1MICRO	2	$0.21	$0.42
	0.47 MICRO	1	$0.12	$0.12
	0.3 MICRO	1	$3.26	$3.26
	0.1 MICRO	2	$0.18	$0.36
	4.7 NF	1	$0.22	$0.22
INDUCTOR	47 MICRO	1	$3.52	$3.52
GAN HEMTS	GS66502B	6	$9.26	$55.56
LT8390		1	$11.15	$11.15
FINAL COSTS				$91.31

Heatsinks are not included in Table X because the datasheet for the GS66502B states that the transistor is designed to be cooled on the printed circuit board [30]. However, adding more copper to the source allows for greater thermal performance [30]. There was no need to add a PCB cost to Table X because the team's tasks included running simulations and designing the PCB but not building the circuit. By not including the cost of the PCB fabrication the final costs in Table X is lower than the estimated final cost in Table IX. The following section goes over the estimated, revised, and actual Gantt charts of the project.

Gantt Chart

The following figures, *Figures 3-5,* document our project planning. *Figure 4* and *Figure 5* contain deadlines for the designing, building, and testing stages of the project. Each design phase begins with a preliminary design that we must do. On the deadline we meet to discuss each other's design and formulate a final design for that design iteration. They cover the ten weeks of EE 461 and the ten weeks of EE462. *Figure 6* shows a legend for the Gantt charts. Orange lines indicate that task belongs to Brian to complete. Red lines indicate that Juan has those tasks. Green lines means both team members must cooperate to complete the task. The deadlines listed on *Figures 3-5* show as blue triangles while the graduate icon indicates instructor feedback.
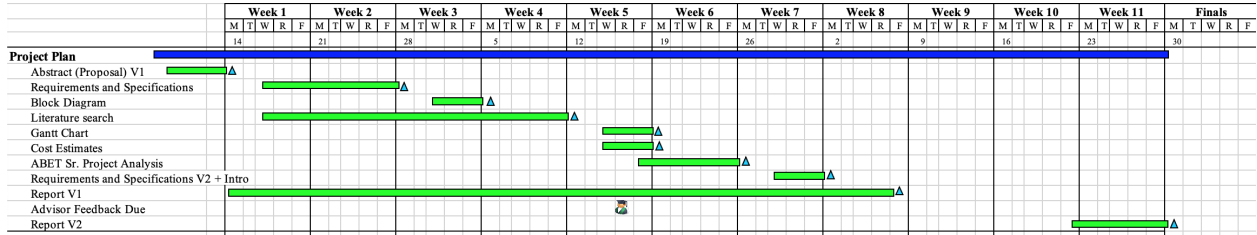
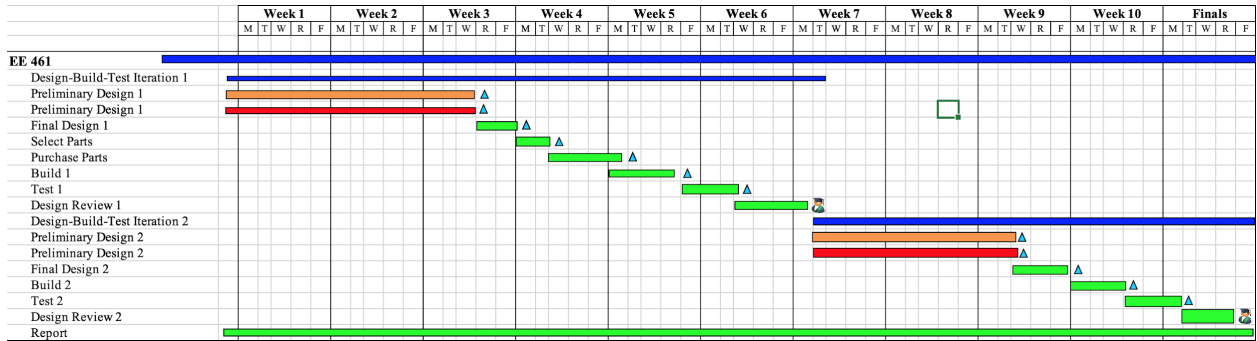*FIGURE 3:* DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 460)

FIGURE 4: DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 461)
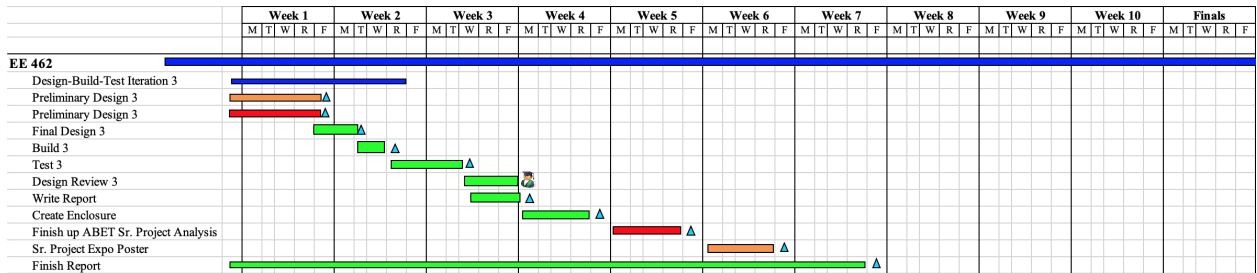

FIGURE 5: DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 462)
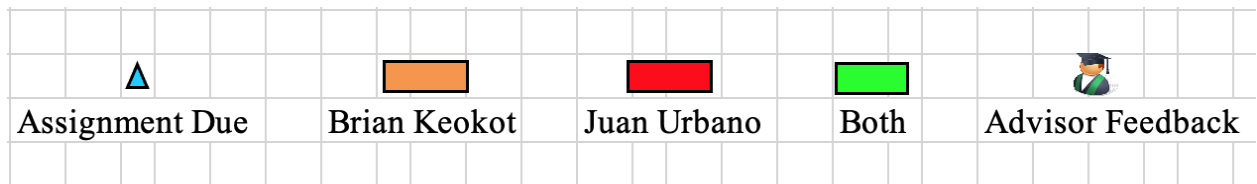
FIGURE 6: DC-DC BUCK BOOST CONVERTER GANTT CHART LEGEND

EE461 REVISED AND ACTUAL COMPARISON
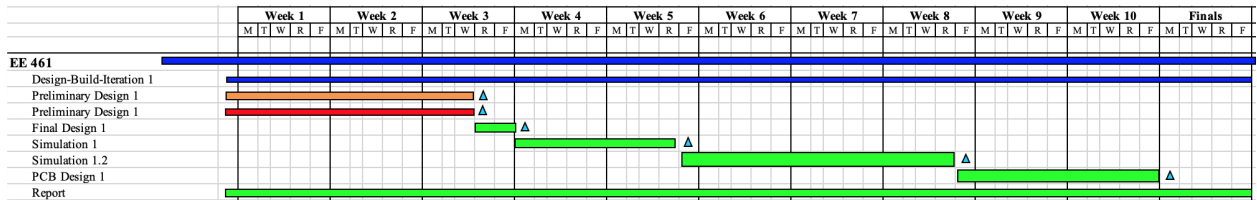
FIGURE 7: REVISED DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 461)
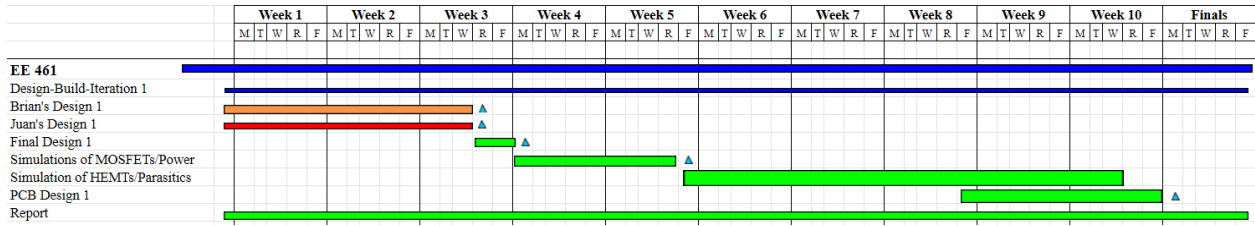
FIGURE 8: **ACTUAL DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 461)**

When creating the original EE461 Gantt Chart during EE460, we hoped for a situation that the pandemic would be over, and we could continue our senior project in person. Unfortunately, the pandemic continued so we revised our timeline to work in a virtual environment. Instead of purchasing parts, building, and testing, we decided, using advice from our advisor, to simulate longer to understand what the DC-DC converter components do and create realistic simulations for future continuations of this project.

Comparing the actual Gantt Chart to the revised one, simulation of the HEMTs and parasitics took longer than expected. The simulation showed problems we did not account for in extreme cases (see Chapter 5 and Appendix B for further details), so more time simulating allowed for a more accurate PCB design.

EE462 REVISED AND ACTUAL COMPARISON
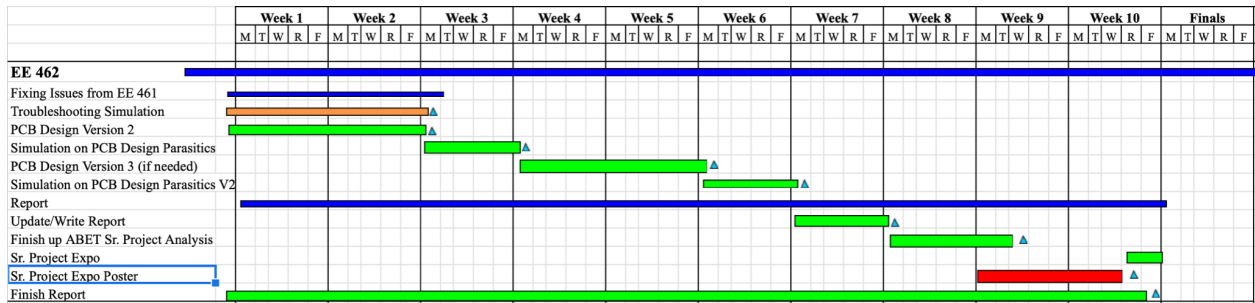
FIGURE 9: **REVISED DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 462)**
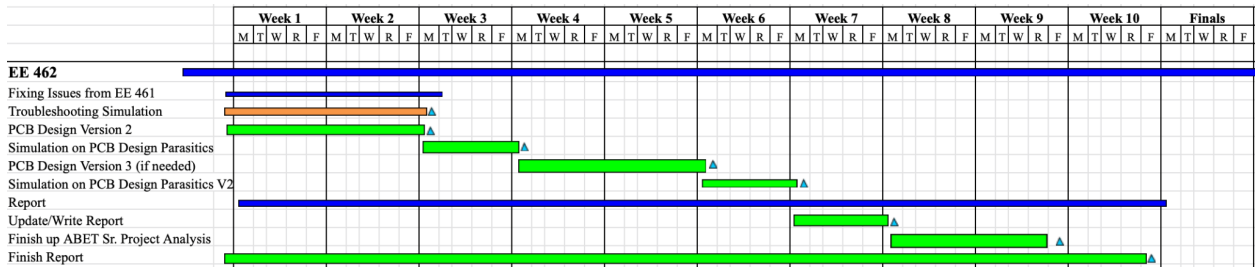
FIGURE 10: **ACTUAL DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 462)**

As with the original EE462 chart, we hoped that we could test a final design in person. This modification of the Gantt Chart shows the PCB design and how long it took for the group members to complete. The members of the project worked on finishing up the simulations from last quarter, which they finished by

the 3rd week of the quarter. From there, the PCB design became the main focus of the quarter, emphasizing on return paths, enough pour space for the transistors, and other various factors.

Comparing the two Gantt charts, we see that the PCB design took longer than expected, as project members have few experiences with PCB design. The project expo listed on the Gantt Chart did not occur, so a poster was not created for this project.

Chapter 5: Simulations

Chapter 5 explains the initial designs from Brian and Juan, along with a first collaborative design later adding parasitic effects. After looking at parasitics effects, HEMTs replace MOSFETs as the HEMTs reduce switching losses of the system. HEMTs achieve this, because their turn-on times are four times faster than MOSFETs and their turn-off times are about twice as fast with the same $R_{DS(ON)}$ values. Lastly, the PCB layout shows that replacing the MOSFETS with HEMTs did not affect our specification of keeping the PCB in a 6" by 6" package. The HEMTs are slightly bigger than the MOSFETs Serres use due to their designed cooling systems. The PCB design receives further elaboration in Chapter 6: PCB Design and Layout located on page 22 of this report.

Brian's Initial Design
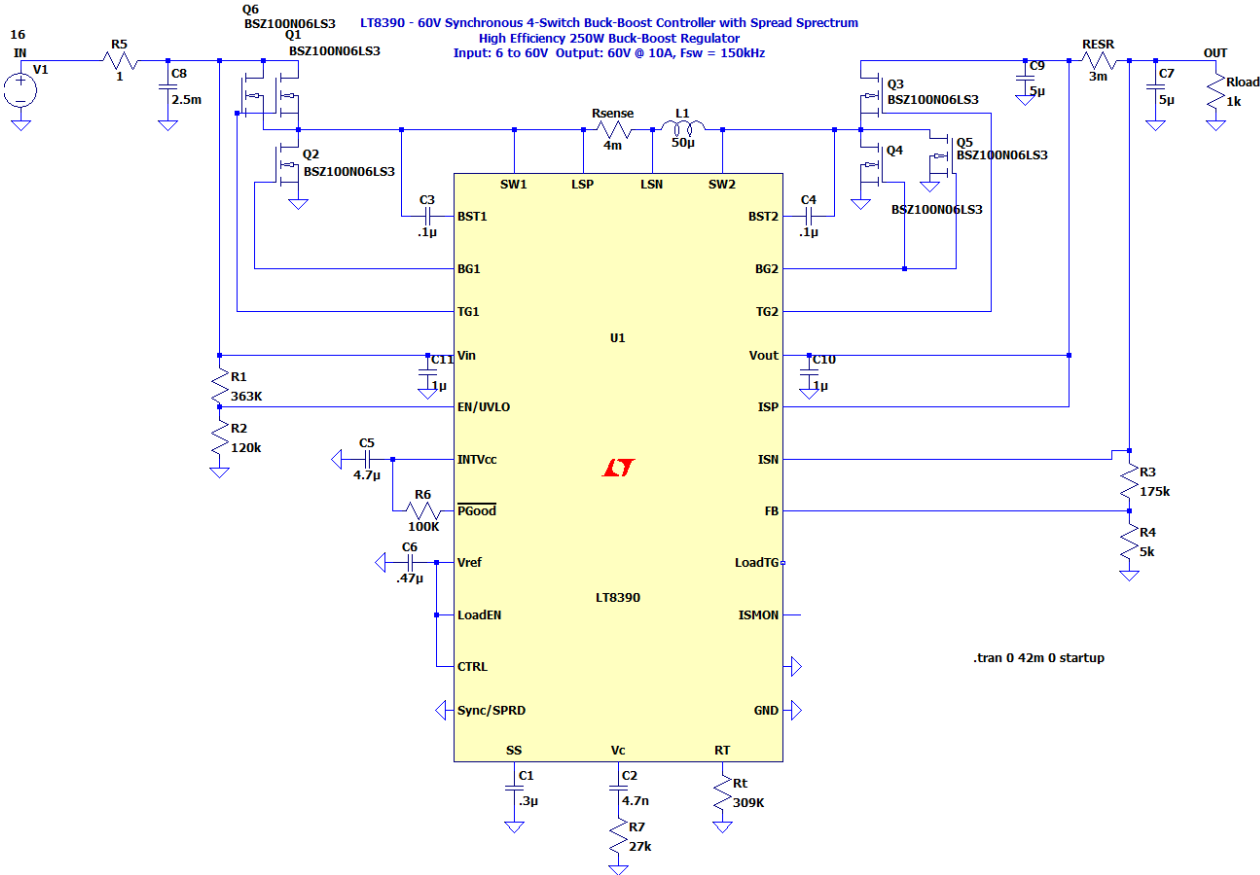
Figure 11: Serres's Final Design of the LT8390 Controller with slight modifications

The original plan of Brian's first few designs was to simulate a working LT8390 model. For the first few simulations, the output voltage did not reach the desired specification of 36 Volts. After many unsuccessful attempts to create a working simulation from scratch, Brian utilized Serres's final design as a starting point. Once Serres's base simulation worked, the goal was to change certain values and understand what Serres did right and wrong.

Juan's Initial Design
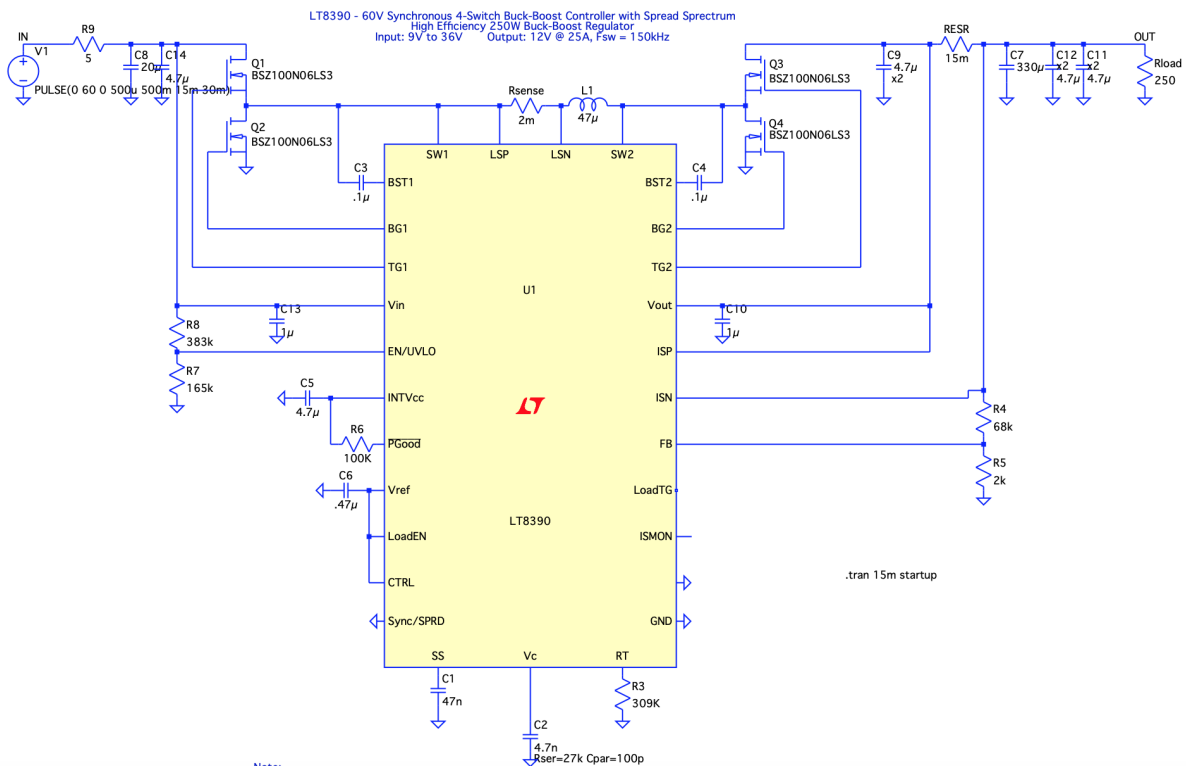
Figure 12: Bolla's Final Design of the LT8390 controller with slight modifications

The goal for Juan's first designs was the same as Brian's goal, to simulate a working DC-DC converter using the LT8390 controller and understand how previous iterations worked. After a few unsuccessful attempts at reaching the desired output voltage of 36 ± 1 V from circuits designed from scratch, Juan used Bolla's design as a reference and began analyzing how the circuit worked by changing values to see how the circuit worked. Through this analysis Juan found power issues that Serres identified and corrected in Juan's iteration of the circuit.

First Design
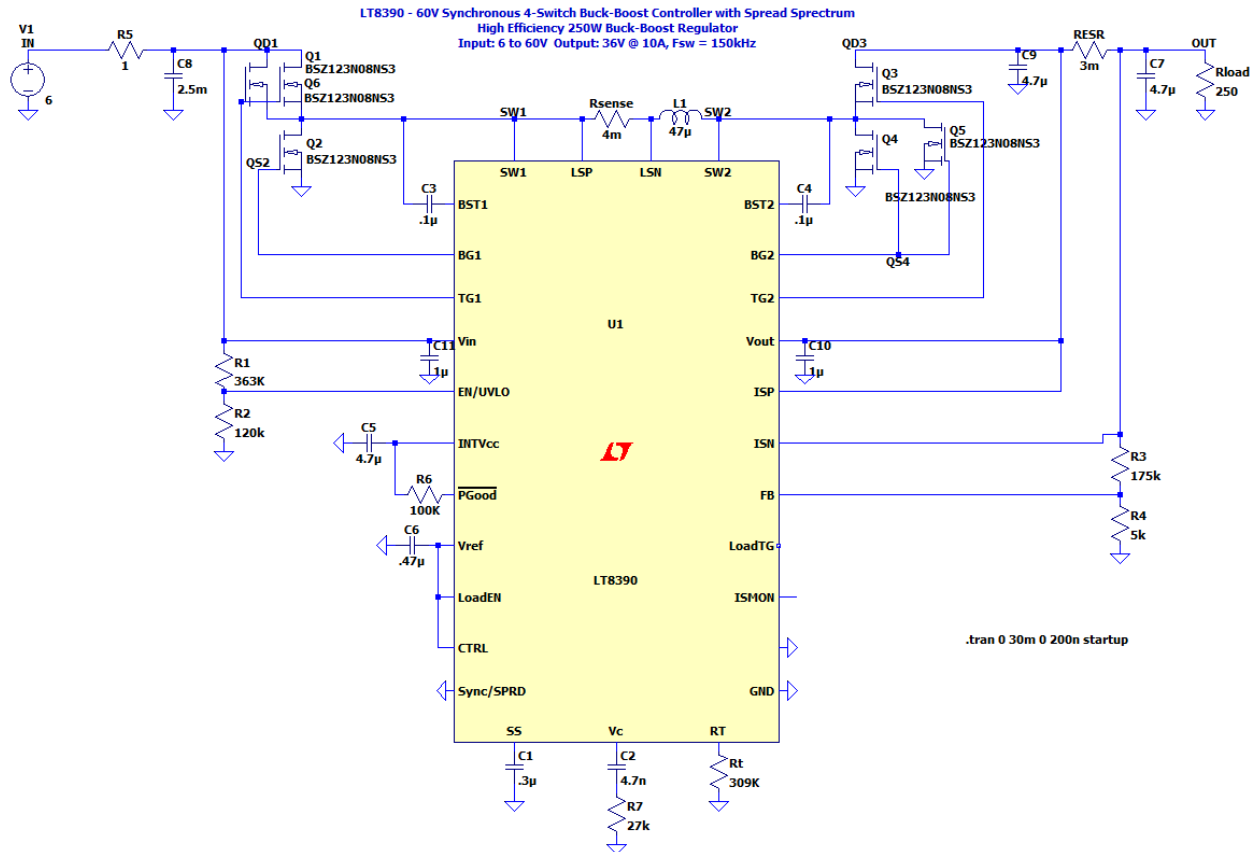
Figure 13: First Design of the LT8390 Controller

Brian decided on changing the MOSFET used by Serres to the BSZ123N08NS3 [31], as the new MOSFETs provided a higher $R_{DS(ON)}$. This change tried to lower the power dissipation in the MOSFETs, which Serres' current MOSFETs show. $R_{DS(ON)}$ increases the conduction loss of the circuit, but lowers the switching loss. With such a high switching frequency of 150kHz, the lower switching loss should decrease the overall loss within the MOSFETs. An earlier design includes a capacitor in parallel with the sense resistor, but removed in later iterations as it did not improve the design.
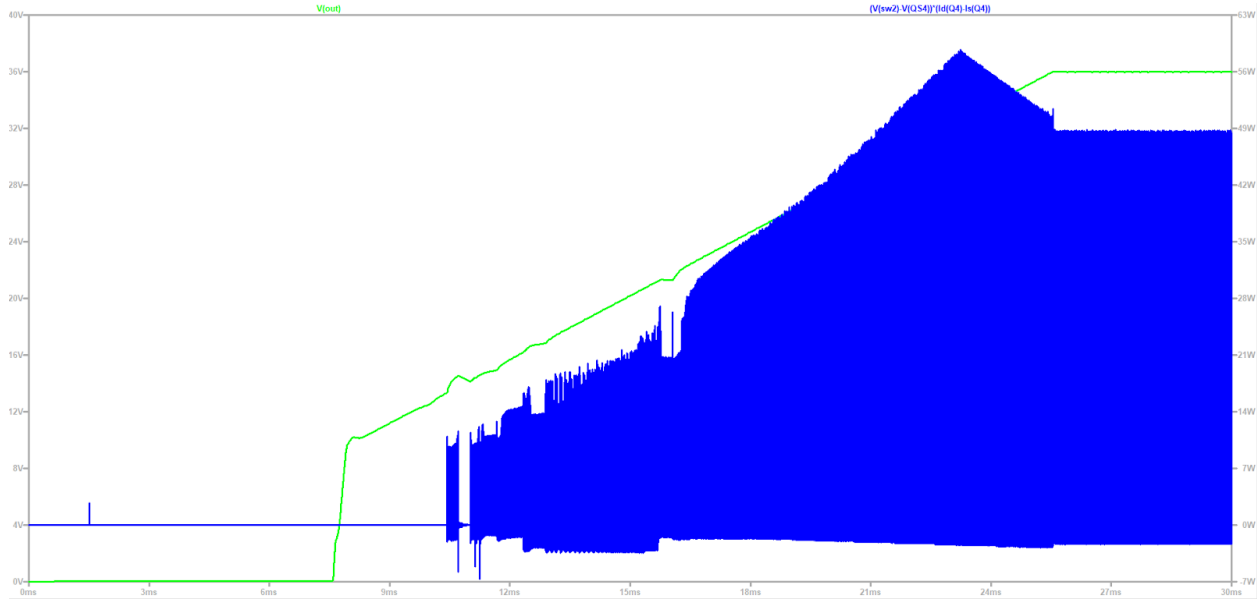
***FIGURE 14:* POWER DISSIPATION IN MOSFET Q4 AND Q5 USING 16 VOLT INPUT AND 250 OHM LOAD**

The figure above shows the MOSFET dissipation of the first design, specifically looking at Q4 and Q5. The MOSFETs show a maximum power dissipation under 133 Watts. MOSFETs Q4 and Q5 show the highest power dissipation, while Q1 and Q6 show the lowest. As the simulations run at an input of 16 Volts and a load of 250 Ohms, the converter changes to different operation modes at the simulated input and load. The converter would begin with buck mode where it receives the input voltage and sends the input voltage of 16 V to the node of SW2. The output voltage reads about 8 V, half of the input voltage. After a couple of milliseconds, the converter switches to buck-boost mode where it slowly begins to boost the input voltage received from SW1. The output voltage reads 18 V during this mode, showing a 2 V increase from the input. The converter then reaches its final operation mode, the boost mode. During this mode, the converter begins to focus on the voltage at the right hand of the circuit, on the location of SW2, Q3, Q4, and Q5, boosting it to the voltage of the voltage divider, R3 and R4. In our case this output voltage should be 36 ± 1 V.

Adding Parasitic Elements

Due to the COVID-19 pandemic, group members could not meet in person during this time. Instead of creating a build and testing it, we discuss with our advisor to create a more realistic simulation. To accomplish this, Juan finds parasitic component values from the datasheets of inductor kits sold by TDK Electronics [27] and capacitor kits sold by KEMET Charged Electronic Components [28]. A Lumen course on AC circuits and electrical technologies attributes to the values for components not listed on the datasheets of the kits [29]. When testing the simulations initially, the DC-DC converter in LTSpice did not run expectantly. When Brian runs the simulation it runs fine, giving both members a more realistic simulation to work with. Stated below are the parasitic values added to certain components.

TABLE XI: PARASITIC VALUES ADDED TO FIRST DESIGN

Components	Value	Series Resistance (ohm)	Parallel Capacitance (F)	Series Inductance (H)
C2	4.7 nF	27 k	100 p	N/A
C1	0.3 uF	3.54	100 p	N/A
C8	2.5 mF	12 m	N/A	0.68 u
C11	1 uF	1.06	100 p	N/A
C5	4.7 uF	0.23	100 p	N/A
C6	0.47 uF	2.26	100 p	N/A
C3	0.1 uF	10.61	100 p	N/A
C4	0.1 uF	10.61	100 p	N/A
C10	1 uF	1.06	100 p	N/A
C9	4.7 uF	0.23	100 p	N/A
C7	4.7 uF	0.23	100 p	N/A
L	47 uF	7	N/A	N/A

From the table, most of the parasitic effects show small differences in simulations. The small differences occur at the steady state AC sinusoidal ripple and when the converter changes mode of operation. Adding these parasitics increases the simulation time of the circuit on LTSpice. These parasitics negatively affect the output voltage slightly. The difference in output voltage between the simulation before and after parasitics is 0.02 V. This difference is not a big negative impact but still affects the design nonetheless.

HEMTS
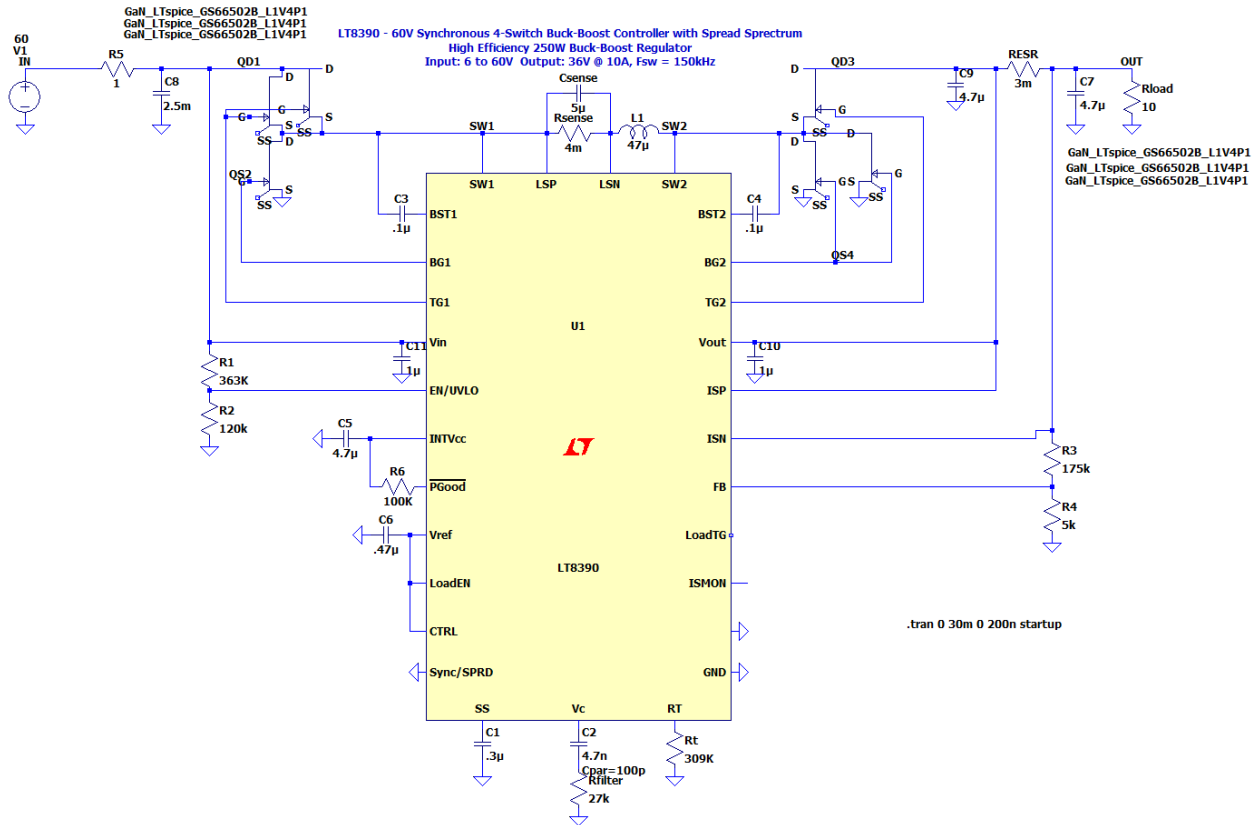
Figure 15: LT8390 Controller with HEMTs

Figure 15 shows the DC-DC converter using the LT8390 Controller using GS66502B HEMTs produced by GaN Systems [30]. This circuit is the latest iteration of Brian and Juan's design. The BSZ123N08NS3 [31] MOSFETs were replaced with these GS66502B HEMTs after consulting with our advisor, Dr. Braun, where he recommended looking into gallium nitride FETs when the team ran into switching losses.
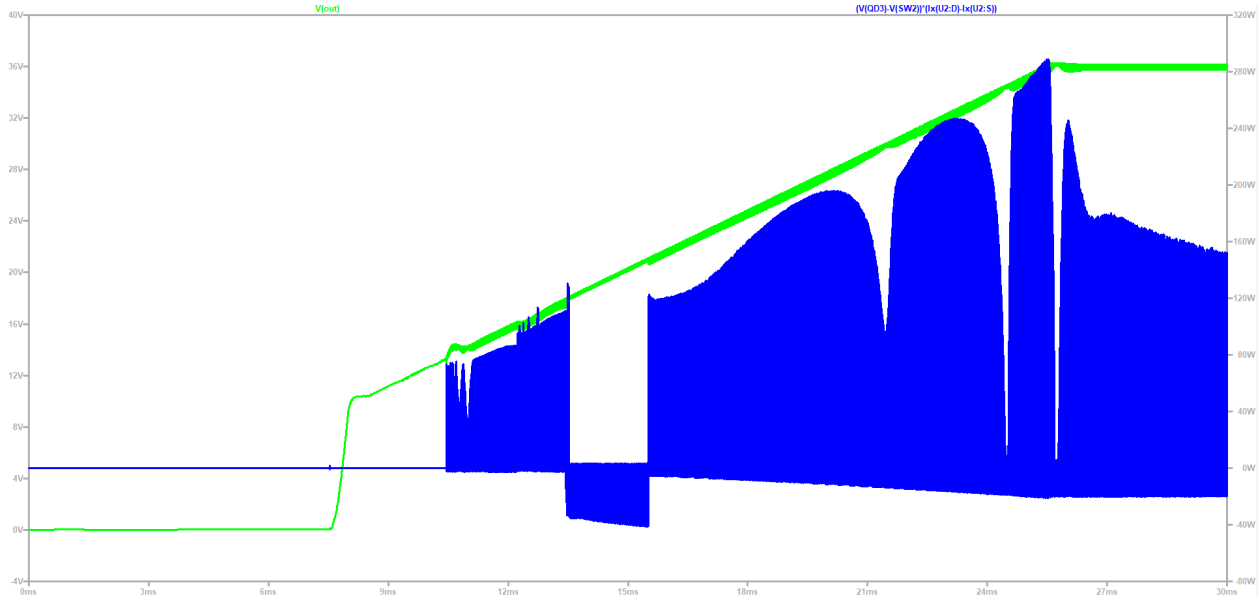
FIGURE 16: **POWER DISSIPATION IN HEMT U2 USING 16 VOLT INPUT AND 250 OHM LOAD**

Following his advice, the team began simulating with the GS66502B HEMT. The power dissipation on the HEMTs vastly outperform the BSZ123N08NS3 MOSFET. The maximum power with the GS66502B HEMT shows higher peaks overall, with peaks ranging from 150-250 W. The MOSFET shows a maximum power peak of 100 W. However, the average power dissipation in each HEMT is smaller than the average power dissipated in each MOSFET. Comparing *Figure 14* and *Figure 16* the improvement is noticeable. With noticeable improvements in power dissipation, the team began working on their PCB design. Chapter 6: PCB Design and Layout documents the team's many iterations of their PCB design.

Chapter 6: PCB Design and Layout

Chapter 6 explains the process of the PCB design in detail. The layout reflects the schematic from the simulations, which then went through multiple iterations to meet safety standards in the industry and finish with a complete and robust layout.

PCB Layout
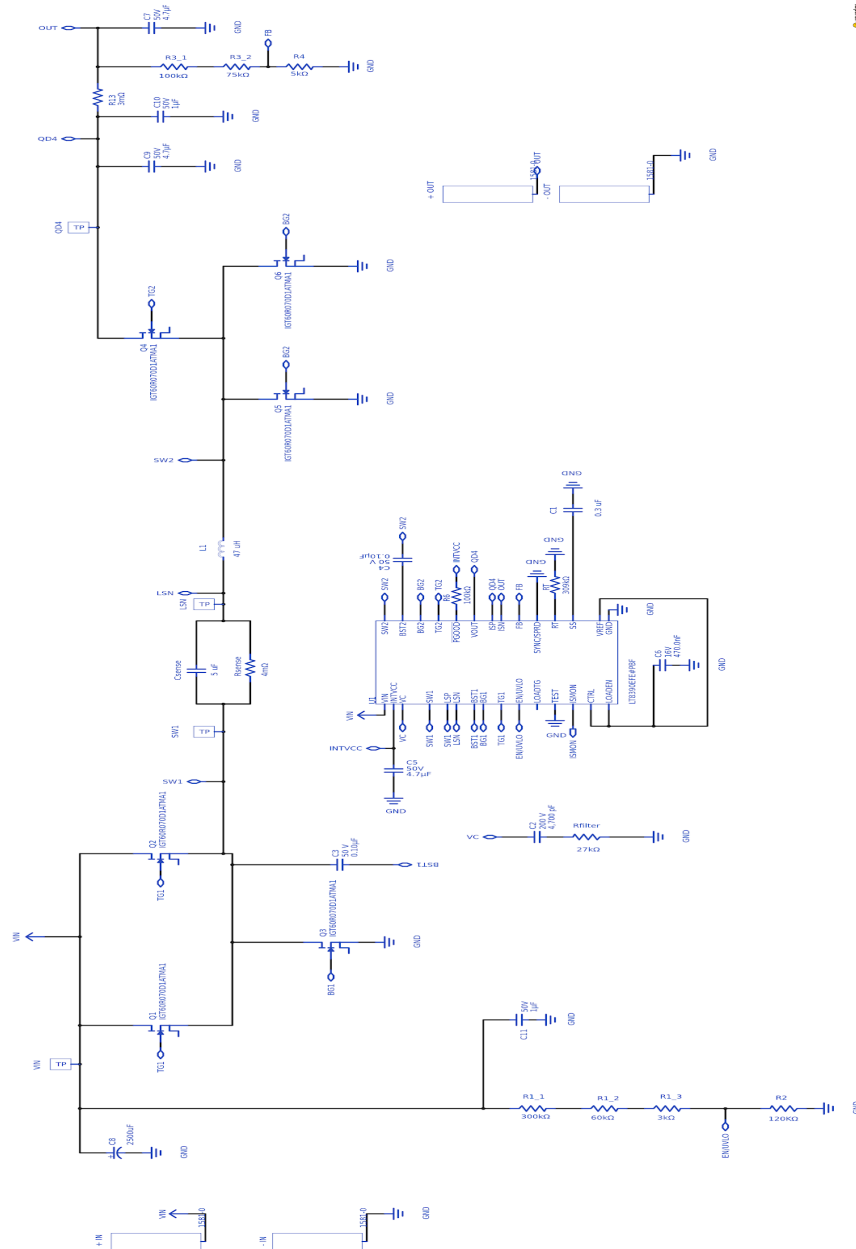
FIGURE 17: SCHEMATIC USED FOR PCB LAYOUT

Figure 17 above shows the full schematic of the project on upverter.com which uses Altium. The figure matches the one from LTSpice on *Figure 15* with a few differences, the main one being the removal of the current limiter resistor, R5 on *Figure 15*. This figure shows only the LT8390 microcontroller and its

connections. The two input connections are on the top left of *Figure 17* and the output connections are on the bottom right. The microcontroller is in the middle of the schematic and the power path is right above the microcontroller.
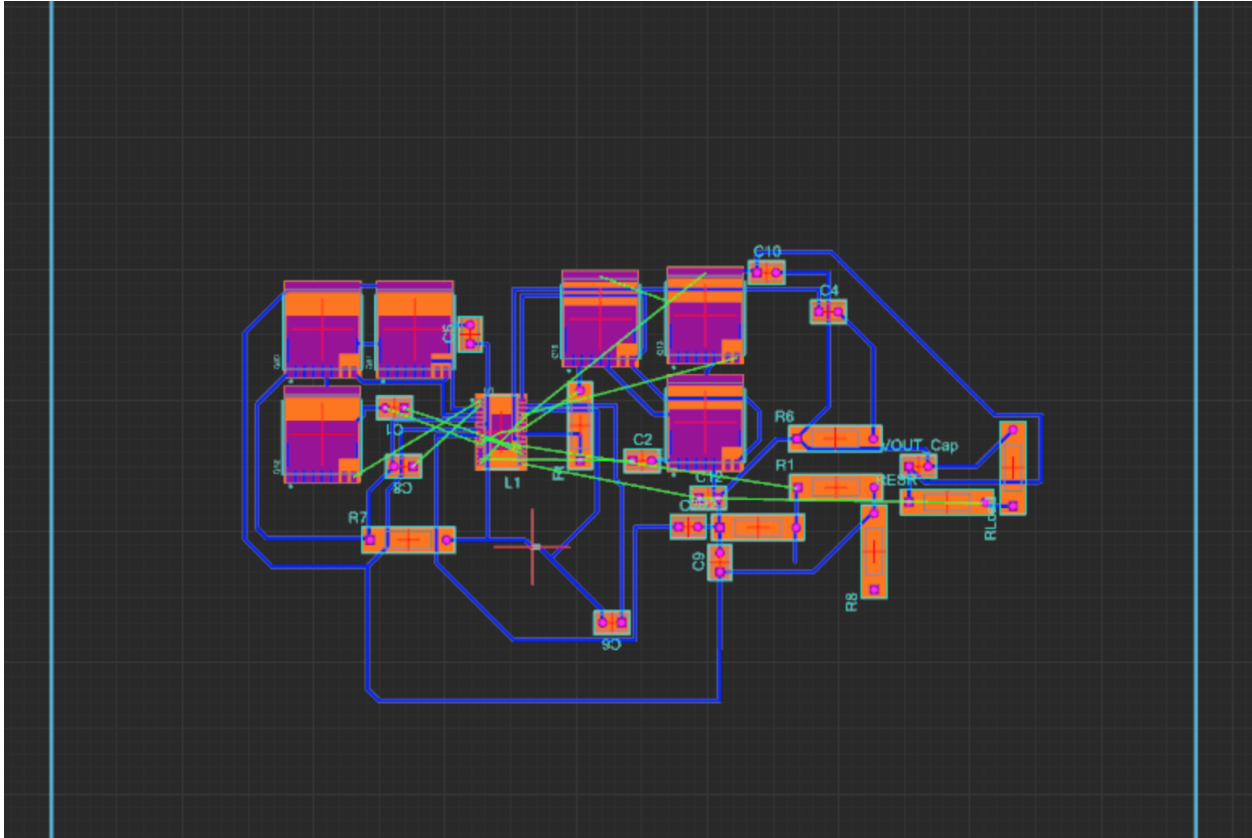
FIGURE 18: **PCB LAYOUT VERSION 1**

Figure 18 above shows the first iteration of the team's PCB layout. As seen above a few nets need to connect to each other so that all nets have connections. During the next quarter the team focuses on finishing up the PCB layout. For the next iteration, the through-hole resistors replace the surface mount resistors. A new inductor model replaces the current model, because the current one is too small and contains an issue, hence the red cross on the layout. The layout in the next iteration undergoes drastic changes with the new additions to the layout, such as pours and ground planes.
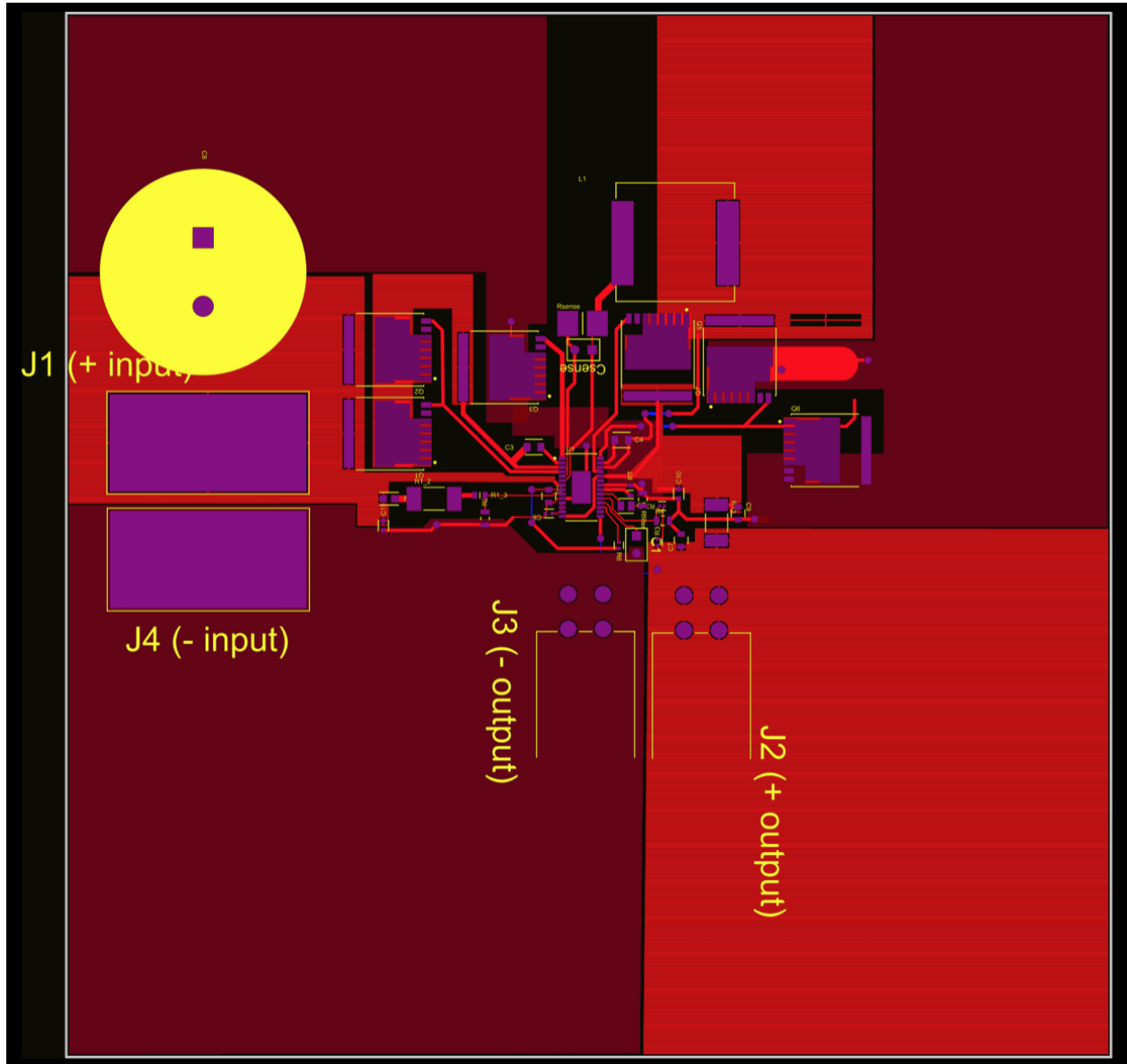
FIGURE 19: PCB LAYOUT VERSION 3

Version 3 of the layout reflects a misunderstanding of how ground planes and pours work. The ground plane and pours do not overlap with each other, as project members thought the two were on the same plane. After this version, members understand that the ground plane is on the bottom while the pours are on the top plane. *Figure 19* shows long traces originating from the LT8390. The long traces create timing problems within the transistors, so the components must move closer in a future design. This iteration focuses on the complete connection of the PCB layout. The return path in this design breaks, as the ground plane and pours are separate in this iteration.
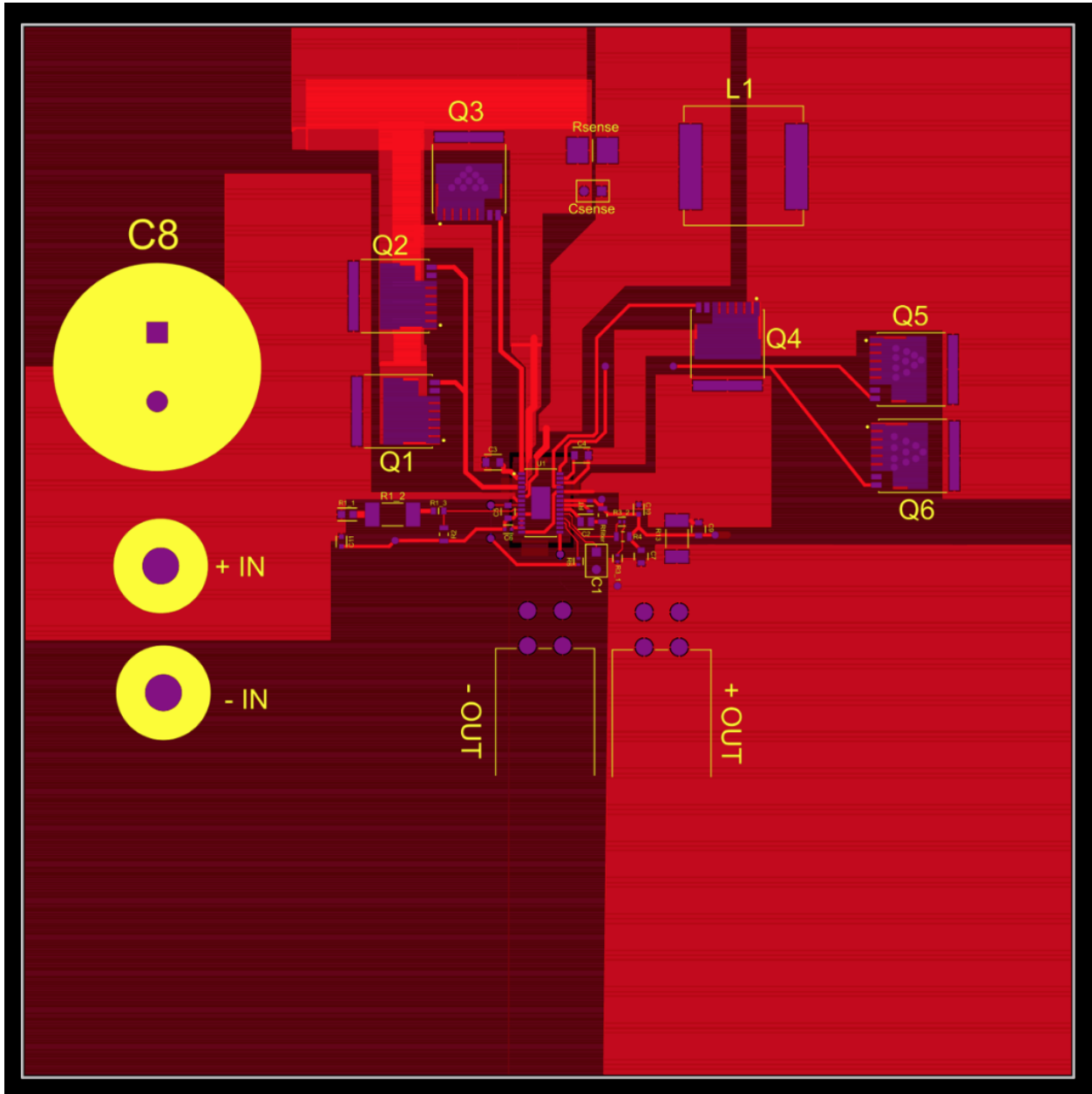
FIGURE 20: **PCB LAYOUT VERSION 7**

Figure 20 shows the 7th iteration of the PCB layout. In this iteration, the main fix consists of the ground plane covering most of the board besides the microcontroller and the pours taking up a large space of the board. Zooming in closely, the digital plane breaks up within the microcontroller and the power plane takes most of the space around the board. Banana plugs were put in the input, as the older inputs are not banana plugs. Changing the input connections means changing the outputs connections, as the outputs should use the same banana plug through holes in the layout. The gate traces on transistors Q1 and Q2 cause desync, as the traces do not branch apart at a further location. The same problem persists for Q5 and Q6, and the final PCB layout fixes it.
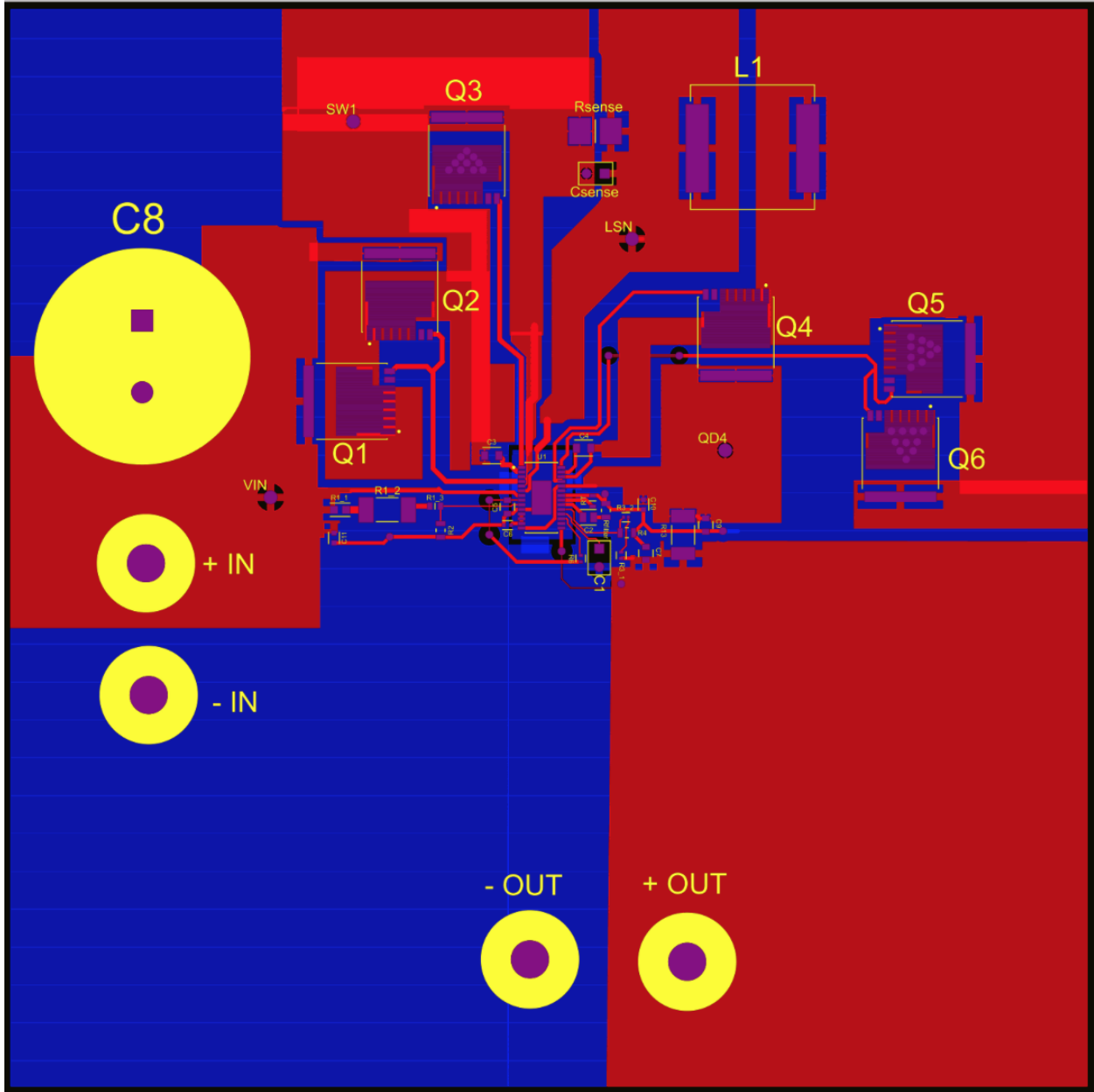
FIGURE 21: **FINAL PCB LAYOUT**

Figure 21 shows the final iteration of the PCB layout. The printed circuit board is 6" long by 6" tall. This iteration fixes the issues found in previous iterations. The output connections are now through-hole banana plug connections just like the input connections. The metal pours now have a 1 mm clearance from the edge of the board to prevent short-circuiting of the board when placed inside an enclosure and the fabrication of the PCB. The gate traces of Q1 and Q2 now have the same length allowing them to switch synchronously. The same goes for the gate traces of Q5 and Q6. The final layout includes test points for troubleshooting.

Future Work

The final PCB layout allows for a square inch for each transistor. However, the tradeoff for this square inch creates a problem with the gate traces. The traces are long, which can cause timing problems for the transistors and matching with the switching frequencies. Another change for future work is the power and digital plane. As of current, the digital plane outlines the LT8390 controller, but having a larger section of the digital plane connecting to the components helps the current flow of the layout.

Chapter 7: Conclusion

This EHFEM project met the goals set from the requirements and specifications that are able to be done virtually. This project report details the process of simulating and creating a layout, with extensive HEMTs power dissipation analysis for an efficient converter.

The LT8390 controller handles the elliptical input without problems and outputs a constant 35.9 to 36.1 voltage for the inverter stage. The power efficiency of the controller met the requirement of 95% with various load tests ranging from 250 to over 1k Ohms.

Results from the extensive simulations can be found in *Appendix B: Simulations* of the report starting on page 43. Appendix B goes into detail about the many simulations done on this project. It contains the .asc files of the final simulation and model of the GS66502B HEMT.

REFERENCES

[1] C. Poly, "Energy," *Energy - Sustainability - Cal Poly*, 2020. [Online]. Available: https://afd.calpoly.edu/sustainability/campus-action/energy/.

[2] N. Serres, *DC-DC Buck-Boost Converter Design for Energy Harvesting from Exercise Equipment*. San Luis Obispo, CA: Digital Commons @ Cal Poly, December 2020.

[3] D. Bolla, "*DC-DC Buck-Boost Converter for Energy Harvesting from Exercise Equipment,*" California Polytechnic State University, San Luis Obispo, June 2019

[3] P. A. Murtaugh and M. G. Schlax, "Reproduction and the carbon legacies of individuals," *Global Environmental Change*, vol. 19, no. 1, pp. 14–20, 2009.

[4] F. Choquet, "Buck-boost converter," U.S. Patent 10,355,596, 01-Jun-2017.

[5] A. Hilario, *ENERGY HARVESTING FROM ELLIPTICAL MACHINES USING FOUR-SWITCH BUCK-BOOST TOPOLOGY.*San Luis Obispo, CA: Digital Commons @ Cal Poly, May 2011

[6] H. Ureh and C. Henry, *DC-DC Converter for Harvesting Energy from an Exercise Bike*. San Luis Obispo, CA: Digital Commons @ Cal Poly, 2009.

[7] A. Forster, *Energy Harvesting From Exercise Machines: Buck-Boost Converter Design*. San Luis Obispo, CA: Digital Commons @ Cal Poly, March 2017.

[8] R. Turner and Z. Weiler, *DC-DC Converter Input Protection System for the Energy Harvesting from Exercise Machines (EHFEM) Project*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2013.

[9] Chu, S. and Yoo, *D. Buck-Boost DC-DC Converter with Input Protection System.* San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2014.

[10] M. Lum and J. Yuen, *Energy Harvesting from Exercise Machines: DC Converter Troubleshooting*. San Luis Obispo, CA: Digital Commons @ Cal Poly, December 2009.

[11] M. Wong, *Energy Harvesting from Exercise Machines - DC-DC Buck Boost Converter (LT3791)*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2014.

[12] B. Burk, R. Bhula, and N. McKay, *Energy Harvesting From Exercise Machines: LT8705 DC-DC Conversion for Elliptical Trainers.* San Luis Obispo, CA: Digital Commons @ Cal Poly, December 2014

[13] R. Ford, C. Coulston, *Design for Electrical and Computer Engineers Theory, Concepts, and Practice*. New York: McGraw-Hill, 2007.

[14] R. Matteo, *Energy Harvesting from Exercise Machines Buck-Boost DC DC Converter with the LT8705 Controller*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2016.

[15] Linear Technology, "60V Synchronous 4-Switch Buck-Boost Controller with Spread Spectrum," LT8390 datasheet, Sept. 2016

[16] "Deeper dive into UPS shipping delays brought on by COVID-19", *KTVU FOX 2*, 2020. [Online]. Available: https://www.ktvu.com/news/deeper-dive-into-ups-shipping-delays-brought-on-by-covid-19.

[17] D. A. Vallero, G. Blight, and T. M. Letcher, "Chapter 6 - Mine Waste: A Brief Overview of Origins, Quantities, and Methods of Storage," in *Waste (Second Edition): A Handbook for Management*, 2nd ed., San Diego, CA: Academic Press, 2019, pp. 129–151.

[18] A. Poor, "Top 6 environmental threats caused by digital electronics," *HPE*, 14-Jan-2019. [Online]. Available:https://www.hpe.com/us/en/insights/articles/top-6-environmental-threats-caused-by-digital-electronics-1901.html.

[19] S. Trac, "How to Maximize Your Equipment Investment," *ClubIndustry*, 30-May-2014. [Online]. Available: https://www.clubindustry.com/sponsored/how-to-maximize-your-equipment-investment.

[20] IEEE Board of Directors, "IEEE Code of Ethics," *IEEE*, 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

[21] C. Yao, X. Ruan, X. Wang and C. K. Tse, "Isolated Buck–Boost DC/DC Converters Suitable for Wide Input-Voltage Range,"in IEEE Transactions on Power Electronics, vol. 26, no. 9, pp. 2599-2613, Sept. 2011, doi: 10.1109/TPEL.2011.2112672.

[22] S. Miao, F. Wang and X. Ma, "A New Transformerless Buck–Boost Converter With Positive Output Voltage," in IEEE Transactions on Industrial Electronics, vol. 63, no. 5, pp. 2965-2975, May 2016, doi: 10.1109/TIE.2016.2518118.

[23] B. S. Revathi and M. Prabhakar, "Non isolated high gain DC-DC converter topologies for PV applications – A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 66, no. December 2016. pp. 920–933, Dec-2016.

[24] Y. Shabany, *Heat transfer: thermal management of electronics*. Boca Raton, Florida: CRC Press, 2010.

[25] S. A. Gorji, A. Mostaan, H. Tran My and M. Ektesabi, "Non-isolated buck–boost dc–dc converter with quadratic voltage gain ratio," in IET Power Electronics, vol. 12, no. 6, pp. 1425-1433, 29 5 2019, doi: 10.1049/iet-pel.2018.5703.

[26] "Thermal management (electronics)," *Wikipedia*, 02-Jul-2020. [Online]. Available: https://en.wikipedia.org/wiki/Thermal_management_(electronics). [Accessed: 11-Oct-2020].

[27] *EPC Sample Kit 2012 Chip Inductors SIMID 1210-H,* B82422X002, Rev. D, TDK, 2012. [Online]. Available: https://www.tdk-electronics.tdk.com/download/175952/81bff3d6384c553b3fe804c1e7adda88/smt-inductors-simid1210-h-inside-view.pdf

[28] *Tantalum Surface Mount Capacitors High Reliability Commercial Off-the-Shelf Polymer Series*, TAN ENG KIT 27, Rev. D, KEMET, 2019. [Online]. Available: https://content.kemet.com/datasheets/TAN_ENG_KIT_27.pdf

[29] L. Learning, "Physics II," *Lumen*, 2021. [Online]. Available: https://courses.lumenlearning.com/austincc-physics2/chapter/23-11-reactance-inductive-and-capacitive/

[30] GaN Systems, "Bottom-side cooled 650 V E-mode GaN transistor," GS66502B datasheet, Apr. 2018

[31] infineon, "OptiMOS 3 Power-Transistor," BSZ123N08NS3 datasheet, Nov. 2009

[32] M. Derrenbacher, *PCB Design and Layout for Hobbyists, Engineers, and Students (Chapter 4 Excerpt.* San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2021

[33] "Upverter Software," *UPVERTER*, 2011. [Online]. Available: https://upverter.com/. [Accessed: 30-May-2021].

APPENDIX A - ANALYSIS OF SENIOR PROJECT DESIGN

PROJECT TITLE: DC-DC BUCK BOOST CONVERTER USING LT8390 CONTROLLER

STUDENT'S NAME: BRIAN KEOKOT, JUAN URBANO

STUDENT'S SIGNATURE: BRIAN KEOKOT, JUAN URBANO

ADVISOR'S NAME: DR. DAVID B. BRAUN

ADVISOR'S INITIALS: DBB

DATE: JUNE 04, 2021

1. **Summary of Functional Requirements**

   The project involves a DC-DC converter that steps up or down the input voltage of 4 to 60 Volts from an exercise machine to an output voltage of 36 +/- 1 Volts. The EHFEM project has the microinverter and exercise machine provided for use for the DC-DC converter.

2. **Primary Constraints**

   Referring back to Chapter 2's requirements and specifications, the LT8390 controller must obtain a 95% threshold of average power efficiency. This proves a huge challenge, as the project must balance between the highest possible efficiency and a good cost for the entire system. The major list of primary constraints is shown in Table I.

   There exist smaller constraints that do not interfere with the constraint of the system itself, but other factors that exist outside. Other constraints of this project include working from home. This group project relies on communication and meeting, but due to the current pandemic the team members cannot meet. Working from home limits collaboration that can be done as well as the way group members can share information. The pandemic presents the challenge of electronic components not arriving within a reasonable period [16]. Team members are unable to meet in person due to the pandemic but meet via Zoom instead. Team members can potentially meet in the coming months but not every team member lives in the San Luis Obispo area. Time management hinders the project greatly. Team members lack the equipment that the Cal Poly Electrical Engineering department provides. Not all team members own the lab equipment available at Building 20 of the university.

3. **Economic**

   Costs accrue in the middle of the project's life cycle, because, at this point, most of the development happens. During development parts are purchased. Benefits occur throughout the project's life cycle but concentrate primarily toward the end of the spectrum. As testing occurs, the developers discover what works and what does not. The benefits apply to the consumer, because they may benefit from all the R&D, if they decide to purchase the system. Team

members pay for this project as well as the company who donated the EFHEM exercise machine. Table IX above provides the estimated cost of the project, $180.43, and Table IX provides the labor costs, $23,813 per team member [13]. Additional equipment costs include software used, such as EAGLE to create PCBs. This additional cost is not added to the equipment list because EAGLE software requires a student license. The project earns money by providing a high enough efficiency to save gyms and the Cal Poly Recreation Center money on their power-utility bill that make it worth their investment in the project [1]. The project takes nine months to complete. These nine months include the planning, development, testing, and presentation of the project.

a. *Human Capital*
   The project involves engineers that manufacture and design the controller and components. The users of the elliptical machine generate electricity for the converter, requiring their time and effort while running.

b. *Financial Capital*
   The manufacturing companies create the PCBs required for the LT8390 controller. Other components must be purchased from various companies to assemble the final design.

c. *Manufactured or Real Capital*
   Companies and their workers use soldering tools and machines to create PCBs. They also create various components, such as resistors and capacitors, that assemble the design to reach the required specifications.

d. *Natural Capital*
   The converter consists of silicon and various other elements to process the PCBs.

e. *When and where do costs and benefits accrue throughout the project's lifecycle?*
   The energy converted from the exercise machine cuts down costs and saves utility companies money. However, installing each design into each machine costs large amounts of money. This project saves electricity for the consumer, and over time generates revenue once the project pays for itself.

f. *What inputs does the project require? How much does the project cost? Who pays?*
   The project takes in the input of the user working out on the elliptical machine. The $23,813 estimated project cost includes labor and part costs. The Cal Poly recreation center purchases the design to save electricity and therefore money. Parts paid by the students and the product sold to the recreational center makes the project useful.

The estimated Gantt chart shows the plan for allotted time of EE 461 and EE 462. As the project moves along and reaches completion, an actual Gantt chart of the process compares the two work habits. An in-depth explanation of the Gantt Chart reflects in Chapter 4. Refer to Chapter 4 for further explanation of the planning breakdown. The cost estimates show the potential cost of the project, and the estimated cost predicted in EE 460. The explanation of Cost Estimates reflects in Chapter 4. Refer to Chapter 4 for further explanation of the cost estimates and labor costs.

FIGURE 3

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Finals
	14	21	28	5	12	19	26	2	9	16	23	30

Project Plan
- Abstract (Proposal) V1
- Requirements and Specifications
- Block Diagram
- Literature search
- Gantt Chart
- Cost Estimates
- ABET Sr. Project Analysis
- Requirements and Specifications V2 + Intro
- Report V1
- Advisor Feedback Due
- Report V2

***FIGURE 3:* DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 460)**

FIGURE 4

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Finals

EE 461
- Design-Build-Test Iteration 1
- Preliminary Design 1
- Preliminary Design 1
- Final Design 1
- Select Parts
- Purchase Parts
- Build 1
- Test 1
- Design Review 1
- Design-Build-Test Iteration 2
- Preliminary Design 2
- Preliminary Design 2
- Final Design 2
- Build 2
- Test 2
- Design Review 2
- Report

***FIGURE 4:* DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 461)**

FIGURE 5

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Finals

EE 462
- Design-Build-Test Iteration 3
- Preliminary Design 3
- Preliminary Design 3
- Final Design 3
- Build 3
- Test 3
- Design Review 3
- Write Report
- Create Enclosure
- Finish up ABET Sr. Project Analysis
- Sr. Project Expo Poster
- Finish Report

***FIGURE 5:* DC-DC BUCK BOOST CONVERTER GANTT CHART (EE 462)**

Legend

Assignment Due	Brian Keokot	Juan Urbano	Both	Advisor Feedback

***FIGURE 6:* DC-DC BUCK BOOST CONVERTER GANTT CHART LEGEND**

Cost Estimates

TABLE VIII: DC-DC BUCK BOOST CONVERTER ESTIMATED PARTS LIST

COMPONENT PARTS	VALUES	# OF COMPONENTS	COSTS PER UNIT	TOTAL COSTS
RESISTORS	1.5 M	2	$0.10	$0.20
	510 K	4	$0.50	$2.00
	500 K	2	$3.00	$6.00
	200 K	4	$0.76	$3.04
	50 K	2	$2.77	$5.54
	27 K	2	$1.94	$3.88
MOSFETS	TO-247	8	$4.31	$17.04
CAPACITORS	4.7 MICRO	10	$0.50	$5.00
	1MICRO	2	$0.38	$0.76
	0.1 MICRO	4	$0.24	$0.96
	22 NF	2	$0.36	$0.72
HEATSINK	TO-247 HEATSINK	8	$2.13	$17.04
PCB		3	$30.00	$90.00
LT8390		5	$5.65	$28.25
FINAL COSTS				$180.43

TABLE IX: DC-DC BUCK BOOST CONVERTER LABOR COSTS

LABOR	LABOR COSTS AMOUNT
OPTIMISTIC TIME	360 HOURS
ACTUAL ESTIMATED TIME	420 HOURS
PESSIMISTIC TIME	500 HOURS
APPROXIMATE ENTRY LEVEL SALARY	$56.25/HR
TOTAL LABOR COST	$23,813 PER TEAM MEMBER

4. **If manufactured on a commercial basis:**
    At the moment, no plans exist to produce this device commercially. If the project sells on a commercial basis, the number of devices sold would be towards Precor elliptical machines at any gym that owns them. The EHFEM project can be sold to various gyms around the nation, or even internationally to gym owners. the Cal Poly recreation center. The manufacturing cost of each device approximates to $35 to $40. Each device would sell for $150 to include labor costs. The estimated profit per year approximates to $200 to $300 depending on the frequency of use on the elliptical machines. The cost for the user to operate the device depends on the lifespan of the device. In this case, maintenance cost of the device equates to $20 to cover replacement components and $20 to replace the LT8390 controller. Assuming over 10,000 units are sold, this EHFEM project would net 1.5 million in sales.

5. **Environmental**
    With any electronic project, there exist positive and negative environmental factors to account. Negative environmental factors that come from mining gold and copper used in the electronic device include unwanted waste material, such as cyanide and mercury, that alters landscapes and damages ecosystems [17]. Pollution that comes out of the manufacturing of this device includes the electronic cleaning and treatment that leads to the pollution of local water supplies [18] as well as the increase in electronic waste, known as e-waste. Manufacturing these devices requires numerous electronic components, as seen in Table IX. Unfortunately, some of these parts cannot be recycled at the end of the device's life. These parts contribute to the massive e-waste that our world currently has. The manufacturing of components harms the environment by mining materials required to build the product. Fossil fuels and other energy consumption methods are used to power the converter. All the electronic parts are purchased online and arrive at the team members' homes via mail/shipping. The environmental impacts include extra pollution to our planet caused by the planes and cars delivering the parts. This device which focuses on renewable energy generation helps the sustainability efforts that Cal Poly strives to achieve, helping Cal Poly reach their goal of 85% of renewable energy from carbon free sources [1]. Implementation of this device in exercise machines allows humans to operate gym equipment and know that they exercise and help the world create a safe and clean environment.

6. **Manufacturability**
    The ability to receive parts during a reasonable time marks a predicted challenge of this project. Due to the COVID-19 pandemic, some parts become unavailable or have a long shipping time [16]. The EHFEM project requires only generic PCB fabrication. Manufacturing can include damage to the materials used in the production due to transistors and wiring components. Packaging and distribution can lead to bent pins and damaged components. The input capacitors and MOSFETs must take in 60 Volts for the maximum input voltage, meaning ratings can withstand up to 120 V to account for overshooting and peak to peak ripples. With the PCB design, the through hole input, outputs, and the 2.5 mF capacitor could be faulty due to manufacturing. Assembling the components on the PCB layout would require a lot of time spent, as there are many small components close together.

7. Sustainability

Issues that may arise while maintaining the system include purchasing new parts to replace the faulty ones. The worst-case scenario includes purchasing a whole new device. The device uses the energy the user of gym equipment generates to create an electrical signal that goes back to the grid. Improving the design requires increased efficiency, but a higher efficiency becomes increasingly difficult as the efficiency approaches 100%.

The project must sustain itself for at least 90% of the elliptical machine's life cycle without needing replacement parts. The design may not produce the maximum efficiency after 90% of the elliptical machine's life cycle, as extensive use on elliptical trainers produces lower efficiency. This extensive use causes gyms to replace elliptical trainers every 5-8 years [19]. The project impacts sustainable use of resources by reducing energy consumption and demand needed by the energy harvesting machines. The project would benefit from a screen that displays total energy saved from using the machine. This motivates the user to continue using the exercise machine in the future.

8. Ethical

Ethical issues may arise from the project's design, manufacturing, and usage of the project. The project design must avoid potential safety hazards to the users of the exercise machines. Improper designs and implementations that include a wide voltage and current range could lead to heat spikes that could potentially damage the exercise machine and worse, cause burns to the user. By having a good design this project follows the IEEE Code of Ethics Section I.6 which states, "to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations" [20]. Design of this project follows the ethical egoism route. Ethical egoism states that people should act in their own self-interest. Non-RoHS compliant components are cheaper than RoHS compliant components but negatively impact the environment. In their self-interest, designers should use cheaper parts that get the job done to make a profit. To uphold the IEEE Code of Ethics the designers must use caution when these types of shortcuts present themselves.

Unethical usage of the project has the possibility to violate the IEEE Code of Ethics Section II.7 which states, "to treat all persons fairly and with respect and to not engage in discrimination" [20] because some areas/people may receive discrimination, because not every gym can afford this device. If the EHFEM projects exist at the Cal Poly Recreation Center, Cal Poly could gain an advantage over gyms in the San Luis Obispo region. Gyms without a Precor elliptical machine cannot take advantage of the converter and are unable to benefit from it. The EHFEM device must produce a negative life cycle for a market to exist for it.

To uphold the IEEE Code of Ethics, the system must be safe to use for the public and demonstrate ethical practices. EHFEM does exactly this by having specific requirements to ensure the safety of the user stays unharmed. The user must consent using the application and the harvest of energy by having a notification or warning on the machine or gym membership. The IEEE code of ethics wants the system to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies. EHFEM

accomplishes this task by getting the user to realize their workout using the elliptical machine takes physical energy from the user. It delivers clean energy to the grid. This project upholds IEEE Code of Ethics Section I.1 which states, "... to strive to comply with ethical design and sustainable development practices…" [20] because team members use RoHS compliant parts when developing the device. Although an ethical dilemma does arise from this.

The ethical overview of the project follows a Utilitarian model. As the EHFEM project provides power back to the grid, the project helps reduce the usage of fossil fuel emissions in the environment. The users of the elliptical machine help with keeping renewable and sustainable energy for their local communities. It provides a healthy lifestyle by encouraging the user to exercise. It also encourages gym owners to own an energy harvesting machine to attract users and a long-term investment to reduce energy. Which roots in the premise of psychological egoism, people feel good for doing good especially if it benefits them, because it provides users/customers with a healthy lifestyle and knowing that by exercising they are aiding in energy independence and reducing negative environmental impact.

9. Health and Safety
EHFEM aims to create renewable energy to allow the public to exercise on the energy harvesting machine. No major concerns exist while designing the project, but assembling the project shows a potential danger to the health and safety of project members. Connections of the elliptical machine and the power grid take precaution to avoid danger. The health safety of cardiovascular activity applies, regarding the safety of the user. Reading the elliptical machine's instructions helps guarantee the user's safety. Users must comply with industry standards, such as NEC and IEEE 1547, to keep alterations of the exercise machine from harming the user's health and safety. The device lacks overcurrent protection now; therefore, using the device could damage it. The enclosure specification of this project proves a potential health hazard, as having the entire device within a small space can increase the temperature of the exercise machine. The system proves dangerous if precautions are not kept in mind.

10. Social and Political
The design allows for a social impact on gym communities by showing energy reduction and consumption. As our society begins to consider the environmental impact of sustainable products and energy efficiency, projects like EHFEM will have a large political impact, when the governments need to consider sustainability as our main source of energy. EHFEM represents a project that will move society forward, going towards the idea of sustainability and preserving the environment for generations to come.

This project impacts direct and indirect stakeholders. Direct stakeholders include gym owners, the Cal Poly recreation center, project members, Analog Devices, and our advisor, Professor Braun. The project benefits Analog Devices because this project uses their LT8390 microcontroller. It also benefits Cal Poly, because it pushes them one step closer to achieving their sustainability goal [1]. Cal Poly and gym owners reduce spending on energy at the gym and sending energy back to the grid. However, both must buy the energy harvesting machines to start using them. Project members benefit from learning power electronics and having a senior project to talk to

recruiters for resumes and interviews. Professor Braun works with students to add on his list of successful sustainability projects.

Indirect Stakeholders include gym members, Cal Poly students, part manufacturers, and power utility companies. Gym members and Cal Poly students benefit from a workout and saving energy using the energy harvesting machines. However, gym members and Cal Poly students indirectly pay for the energy harvesting machines with their funding. Part manufacturers show that their components comply with industry standards, and the parts are involved with the project design. Power utility companies obtain renewable energy back to the grid from the energy harvesting machines.

The project favors the larger gym owners and Cal Poly compared to the individual students, as multiple energy harvesting machines saves them money and energy in the long term, while smaller gyms cannot recover the short-term cost within 9 years without significant machine usage. Students and gym members must go to the location to use the machine.

11. Development

The simulation of the converters takes a long time to complete, so time must be allotted to simulate the design on time. Each phase gives a new understanding and goal for the next phase of the project. Planning the project ahead of time requires a literature search and a Gantt chart to stay organized. The project uses the Upverter software [33], so during the project we learned how to use it effectively. The literature search helps obtain sufficient knowledge of the LT8390 controller and components required in designing the final product.

<div align="center">Literature Search</div>

[4] F. Choquet, "Buck-boost converter," U.S. Patent 10,355,596, 01-Jun-2017.

Choquet received the patent on June 1, 2017. This patent helps our project because our senior project includes creating a DC-DC buck-boost converter. This patent helps us understand how Choquet created his converter and may give us ideas on how to create ours. This patent has authority because it's assignee, Dialog Semiconductor (UK) Limited, one of the leading providers of industrial ICs, battery management, and AC/DC power conversion in the United Kingdom. The applicant has also cited IEEE articles.

[5] A. Hilario, *ENERGY HARVESTING FROM ELLIPTICAL MACHINES USING FOUR-SWITCH BUCK-BOOST TOPOLOGY.* San Luis Obispo, CA: Digital Commons @ Cal Poly, May 2011

This thesis paper written by Hilario explains that a four-switch buck-boost DC-DC converter works best with the EFHEM system. Hilario's paper spawned multiple iterations of four-switch buck-boost converter designs including the one in this project. Hilario received his Master's degree in Electrical Engineering and consulted multiple advisors from the Electrical Engineering department at California Polytechnic State University.

[6] H. Ureh and C. Henry, *DC-DC Converter for Harvesting Energy from an Exercise Bike.* San Luis Obispo, CA: Digital Commons @ Cal Poly, 2009.

The project consists of one of the starting points for the Energy Harvesting for Exercise Machine projects. This paper provides insight on how a similar design works at a lower efficiency rating and steps needed to accomplish the project. The authors obtained support from professors in the Electrical Engineering department. Henry has received a Bachelor's in Electrical Engineering and Ureh has received a Master's in Electrical Engineering.

[7] A. Forster, *Energy Harvesting From Exercise Machines: Buck-Boost Converter Design.* San Luis Obispo, CA: Digital Commons @ Cal Poly, March 2017.

This thesis paper explains what our project must iterate on. The Buck-Boost Converter using the LT8390 controller improves Forster's design and uses the microinverter from this design to send power to the electrical grid. Forster has received a Master's degree in Electrical Engineering and has consulted multiple advisors about his project.

[8] R. Turner and Z. Weiler, *DC-DC Converter Input Protection System for the Energy Harvesting from Exercise Machines (EHFEM) Project*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2013.

This project's purpose was to create an input protection system for the EHFEM system. This input protection system connects to the input of the DC-DC converter to protect it from any voltage or current spikes. The LT8390 converter project builds upon this protection system. The authors of this project worked closely with Dr. Braun to ensure a working project and the paper describes it.

[9] Chu, S. and Yoo, *D. Buck-Boost DC-DC Converter with Input Protection System.* San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2014.

This paper explains a part of the EFHEM project that our project uses. It is an input protection system implemented into the EHFEM system by Cal Poly graduates that worked closely with Dr. Braun. This protection system worked with previous EFHEM projects and systems.

[10] M. Lum and J. Yuen, *Energy Harvesting from Exercise Machines: DC Converter Troubleshooting*. San Luis Obispo, CA: Digital Commons @ Cal Poly, December 2009.

The paper explains how the inverter of the EHFEM project works, which connects to the output of the DC-DC Converter. The LT8390 controller project builds upon this Enphase inverter. The authors of this project worked closely with Dr. Braun to ensure a working project and the paper describes it.

[11] M. Wong, *Energy Harvesting from Exercise Machines - DC-DC Buck Boost Converter (LT3791)*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2014.

The paper explains one of the earliest four-switch DC-DC converters of the EFHEM project. This converter used the LT3791 controller and the LT8390 controller project in the future builds upon this design. The author of this project worked closely with Dr. Braun to ensure a working project and the paper describes it.

[12] B. Burk, R. Bhula, and N. McKay, *Energy Harvesting From Exercise Machines: LT8705 DC-DC Conversion for Elliptical Trainers.* San Luis Obispo, CA: Digital Commons @ Cal Poly, December 2014.

This paper shows another version of a four-switch DC-DC converter used for the EFHEM project. This converter uses the LT8705 controller and the LT8390 controller project improves upon this design. The author of this project worked closely with Dr. Braun to ensure a working project and the paper describes it.

[14] R. Matteo, *Energy Harvesting from Exercise Machines Buck-Boost DC DC Converter with the LT8705 Controller*. San Luis Obispo, CA: Digital Commons @ Cal Poly, June 2016.

This paper shows another version of a four-switch DC-DC converter that used the LT8705 controller. The converter design helps the LT8390 controller project improve design and iterations. The author of this project worked closely with Dr. Braun to ensure a working project and the paper describes it.

[15] Linear Technology, "60V Synchronous 4-Switch Buck-Boost Controller with Spread Spectrum," LT8390 datasheet, Sept. 2016

This datasheet provides information for the LT8390 controller pinout, efficiency rating, and more critical information about the controller. The company that wrote the datasheet, Analog Devices, specializes in data conversion, signal processing, and power management technology. They manufacture semiconductors, giving them credibility for the datasheet information.

[21] C. Yao, X. Ruan, X. Wang and C. K. Tse, "Isolated Buck–Boost DC/DC Converters Suitable for Wide Input-Voltage Range," in IEEE Transactions on Power Electronics, vol. 26, no. 9, pp. 2599-2613, Sept. 2011, doi: 10.1109/TPEL.2011.2112672.

This source talks about DC-DC Buck-Boost Converters for a Wide Input-Voltage Range. Since the project consists of an input voltage range of 4-60 V, this article can help understand how to take the input range in. The IEEE journal article can provide reliable information from knowing the background of the authors. The authors research in soft switch DC-DC converters and renewable-energy-generation systems. The authors received Ph.D. degrees in Electrical Engineering around various institutions.

[22] S. Miao, F. Wang and X. Ma, "A New Transformerless Buck–Boost Converter With Positive Output Voltage," in IEEE Transactions on Industrial Electronics, vol. 63, no. 5, pp. 2965-2975, May 2016, doi: 10.1109/TIE.2016.2518118.

This source talks about a DC-DC converter with a positive output voltage. By having a positive output voltage the converter can work with a wider range of outputs. Since the project consists of outputting 36 V ± 1 V, this article can help us understand how to configure our converter to have a positive output. This IEEE journal article provides helpful information about the authors. The authors have received their M.S. and Ph.D. in Electrical Engineering. Part of Xi'an Jiaotong University's State Key Laboratory of Electrical Insulation and Power Equipment. They research and lecture at the university.

[23] B. S. Revathi and M. Prabhakar, "Non isolated high gain DC-DC converter topologies for PV applications – A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 66, no. December 2016. pp. 920–933, Dec-2016.

This source reviews non-isolated DC-DC converters for PV applications. It reviews the performances of various converter stages because the efficiency depends on them. Since the project consists of the converter meeting a minimum of 95% efficiency, the review of different converter topologies may point us to the right direction when creating ours. Ph.D. electrical engineering professors from VIT University wrote this review article. The authors cite various IEEE articles in their review.

[24] Y. Shabany, *Heat transfer: thermal management of electronics*. Boca Raton, Florida: CRC Press, 2010.

This book provides and explains different ways to manage heat in electronics such as heat sinks and advanced cooling technologies. The project temperature does not exceed 120 ℉, part of our project's specification and by reading this book allow different approaches to reach this specification. The author has received his Ph.D. in mechanical engineering from Stanford University and works as a professor in the Mechanical Engineering department at San Jose State University.

[25] S. A. Gorji, A. Mostaan, H. Tran My and M. Ektesabi, "Non-isolated buck–boost dc–dc converter with quadratic voltage gain ratio," in IET Power Electronics, vol. 12, no. 6, pp. 1425-1433, 29 5 2019, doi: 10.1049/iet-pel.2018.5703.

This article talks about a non-isolated DC-DC buck-boost converter that reached an efficiency of 94.7%. One specification for the project includes the converter meeting a minimum 95% efficiency. By reading this article we may get ideas on how to construct our converter. The authors cited several IEEE articles and worked with the Swinburne University of Technology in Australia.

[26] "Thermal management (electronics)," *Wikipedia*, 02-Jul-2020. [Online]. Available: https://en.wikipedia.org/wiki/Thermal_management_(electronics). [Accessed: 11-Oct-2020].

This Wikipedia article talks abouts thermal management in electronics. One of the project's specifications include the converter not exceeding 120 ℉. Reading this article, we might find different applications that can help us meet this specification.

APPENDIX B - SIMULATIONS

This appendix of simulation shows the results of certain portions of the project. At the start of the appendix, the simulations reference the initial designs, Figure 12 and 13, of the project members. Once the MOSFETs change, the power dissipation simulations refer to Figure 15.
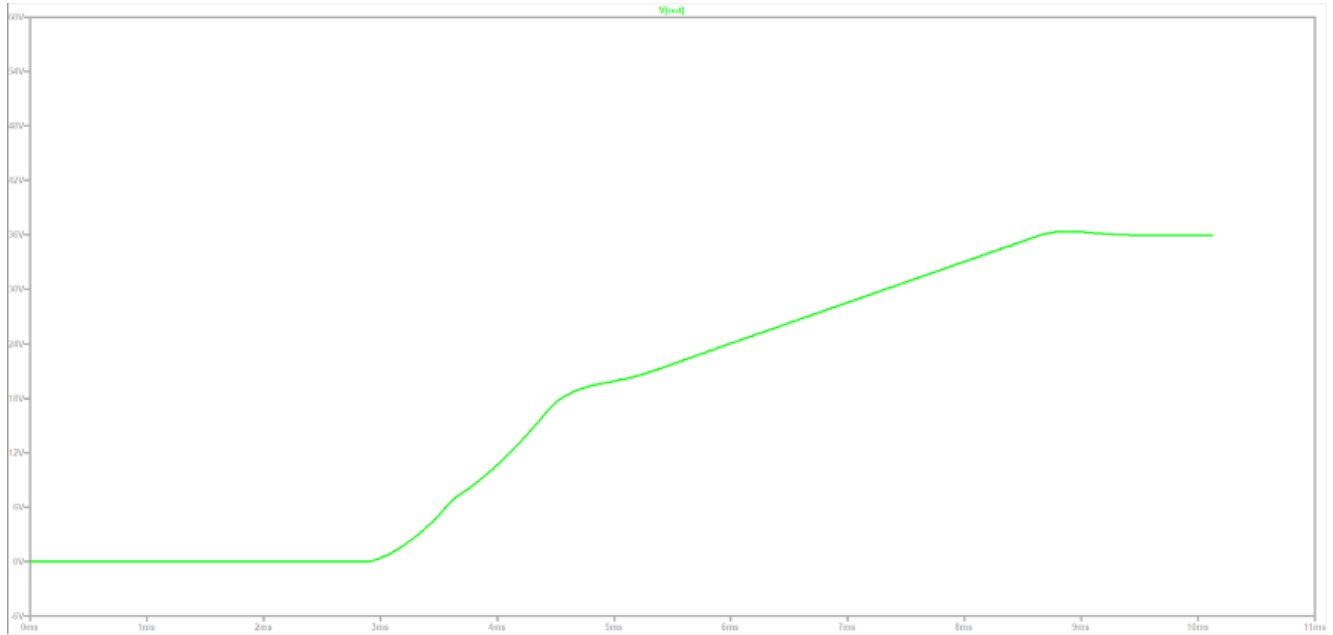
***FIGURE 22:* FIRST SIMULATION USING MODIFIED SERRES'S VALUES**

This first working simulation showed an output voltage of 36 volts within 16 milliseconds, which was the desired goal of the simulation. The simulation goal was to understand how the LT8390 converter reaches the output voltage. Serres' values were modified and adjusted to obtain a lower AC output voltage sinusoidal waveform than his final design. However, the value obtained from modifying resulted in a larger AC output waveform. Simulations continued until the first design, changing values and components to obtain the lower AC output voltage sinusoidal waveform.

FIGURE 23: **CHANGING MOSFETS USING SERRES'S VALUES**

Between the last simulation and this one, multiple simulations occurred that did not result in any progress. Components modified resulted in extreme AC output voltage waveforms, which did not meet the required specification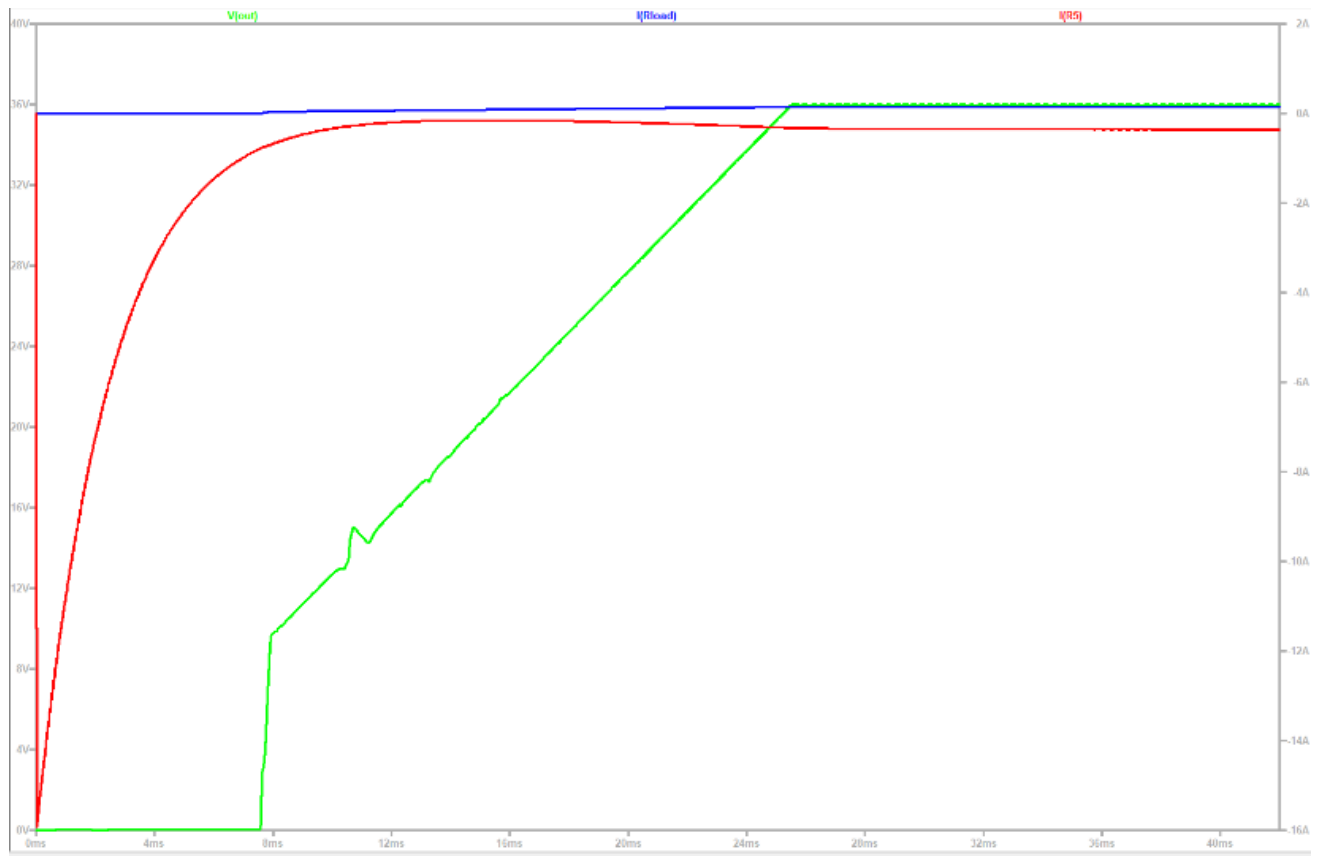s. Instead, the capacitive and resistive components of Serres's design were slightly modified and the MOSFETs were swapped with different ones. The replaced MOSFETs shows better soft switching values and a lower AC voltage waveform. Looking at *Figure 23*, the voltage waveform showed a tiny AC sinusoidal waveform, which met one of the requirements.

The next few figures below showed the MOSFET and HEMT power dissipations of the first design. The figures below, *Figures 24-26*, show the power dissipation of the MOSFETs. The MOSFETs do not perform well with power dissipation. *Figures 27-29* show the power dissipation of the HEMTs. Although the power dissipation in the HEMTs have a higher amplitude, the largest reaching 250 W, each HEMT outperforms the power dissipation of each MOSFET.

FIGURE 24: **POWER DISSIPATION IN MOSFET Q1 AND Q6 USING 16 VOLT INPUT AND 250 OHM LOAD**
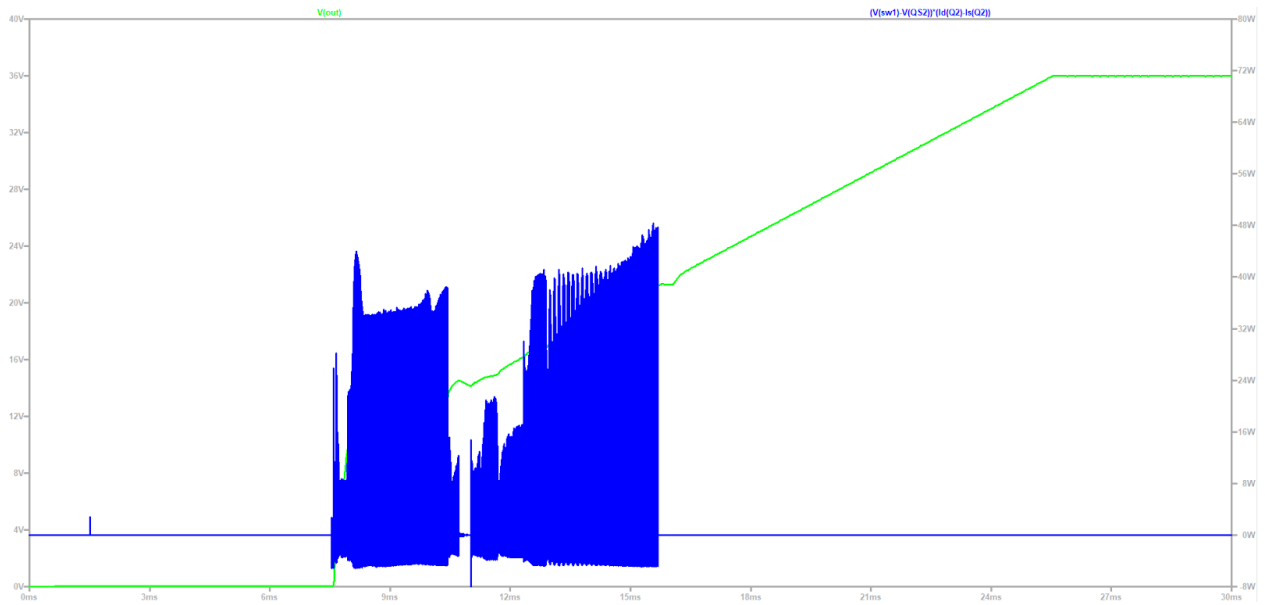
FIGURE 25: **POWER DISSIPATION IN MOSFET Q2 USING 16 VOLT INPUT AND 250 OHM LOAD**
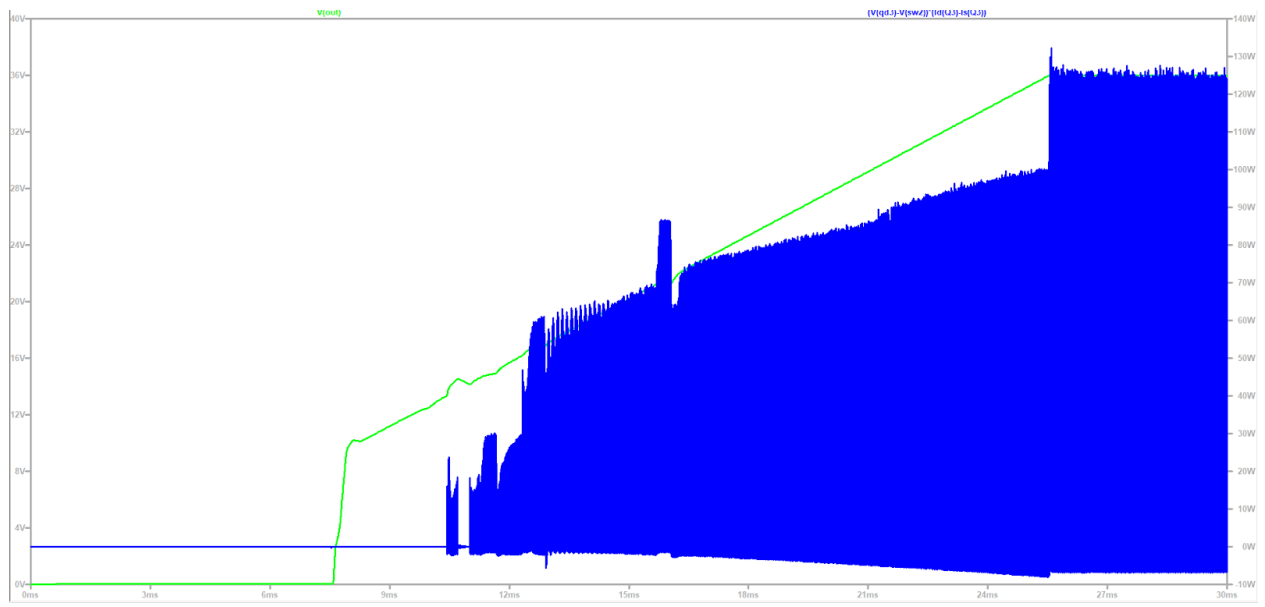
FIGURE 26: **POWER DISSIPATION IN MOSFET Q3 USING 16 VOLT INPUT AND 250 OHM LOAD**
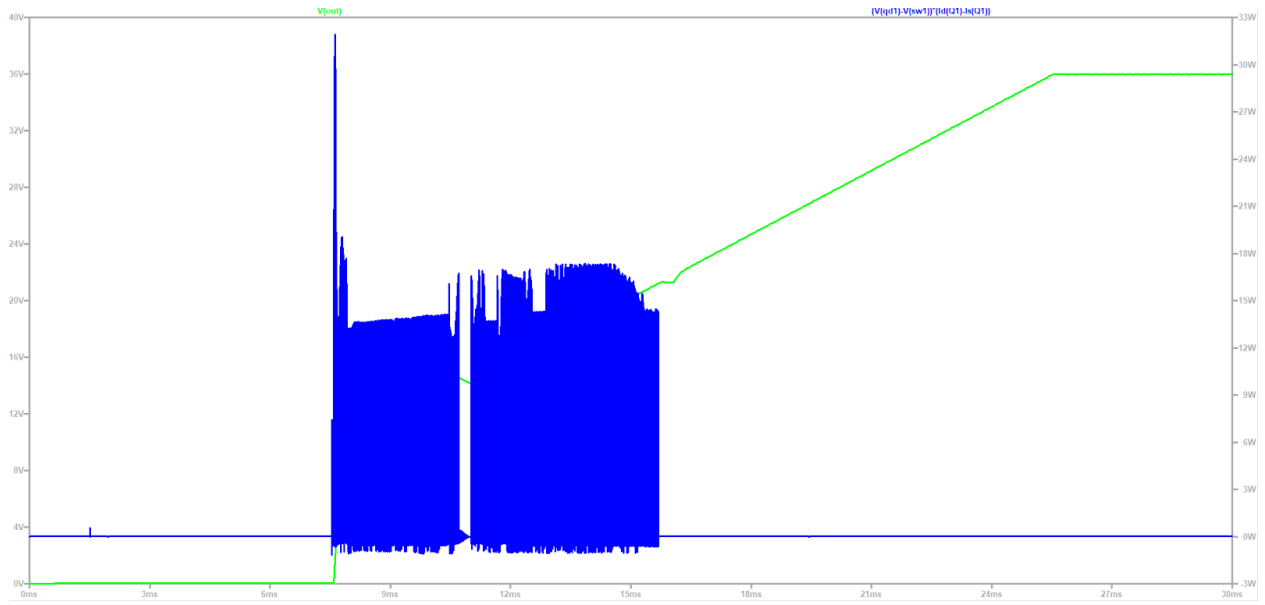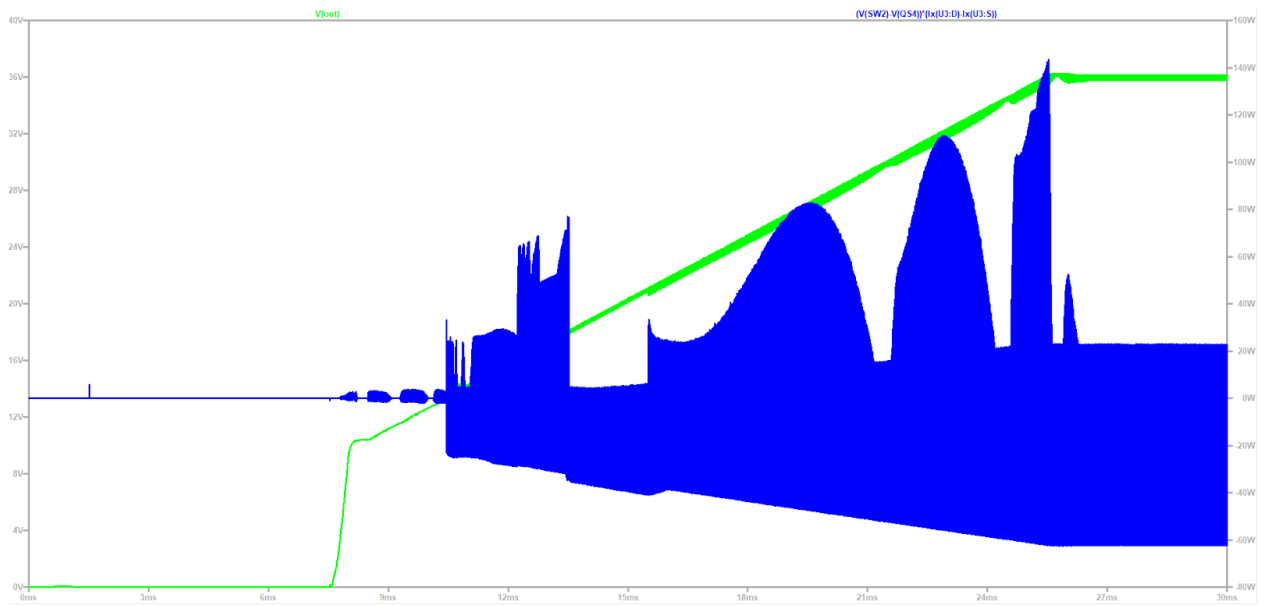

FIGURE 27: **POWER DISSIPATION IN HEMT U3 AND U4 USING 16 VOLT INPUT AND 250 OHM LOAD**
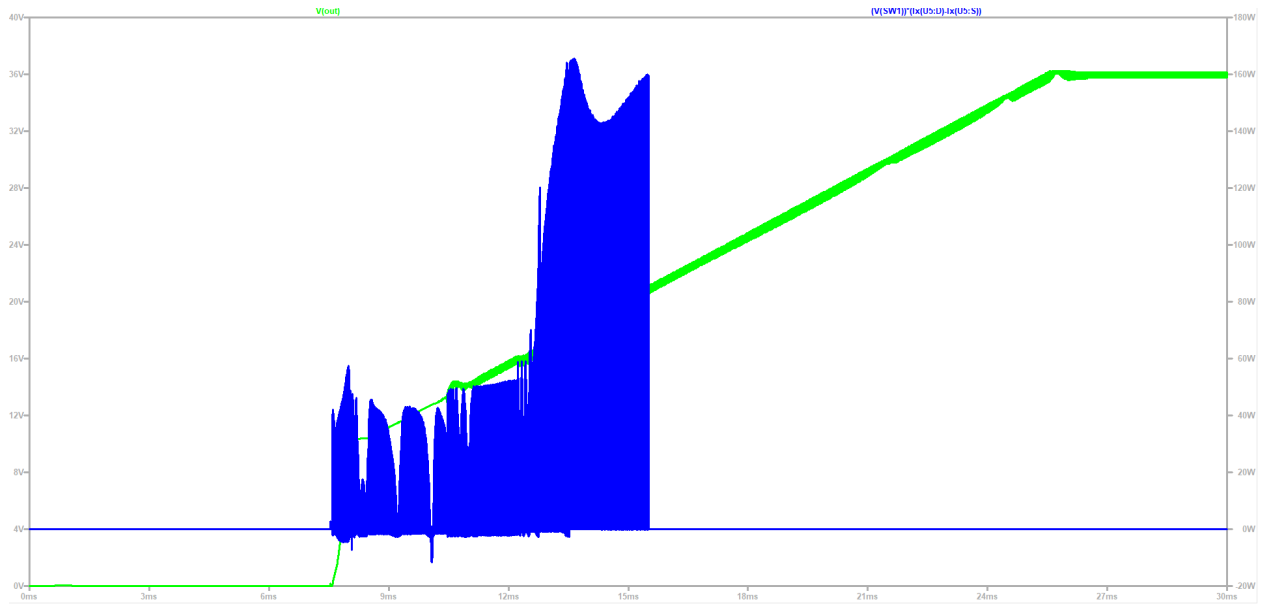
FIGURE 28: **POWER DISSIPATION IN HEMT U5 USING 16 VOLT INPUT AND 250 OHM LOAD**
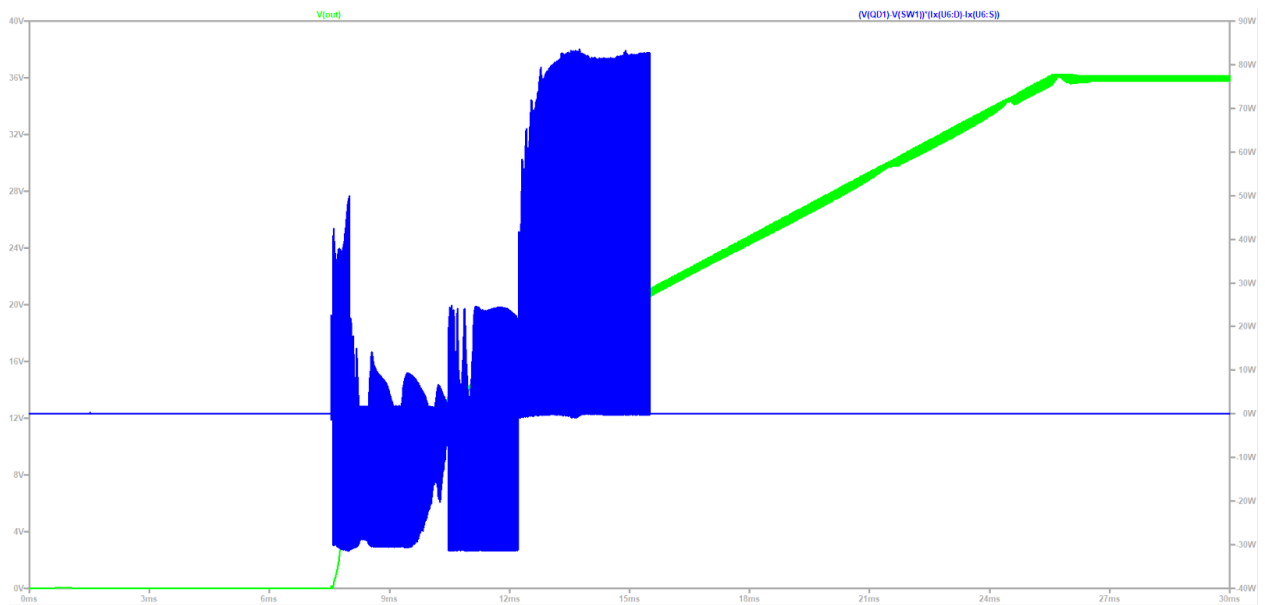
FIGURE 29: **POWER DISSIPATION IN HEMT U6 AND U7 USING 16 VOLT INPUT AND 250 OHM LOAD**
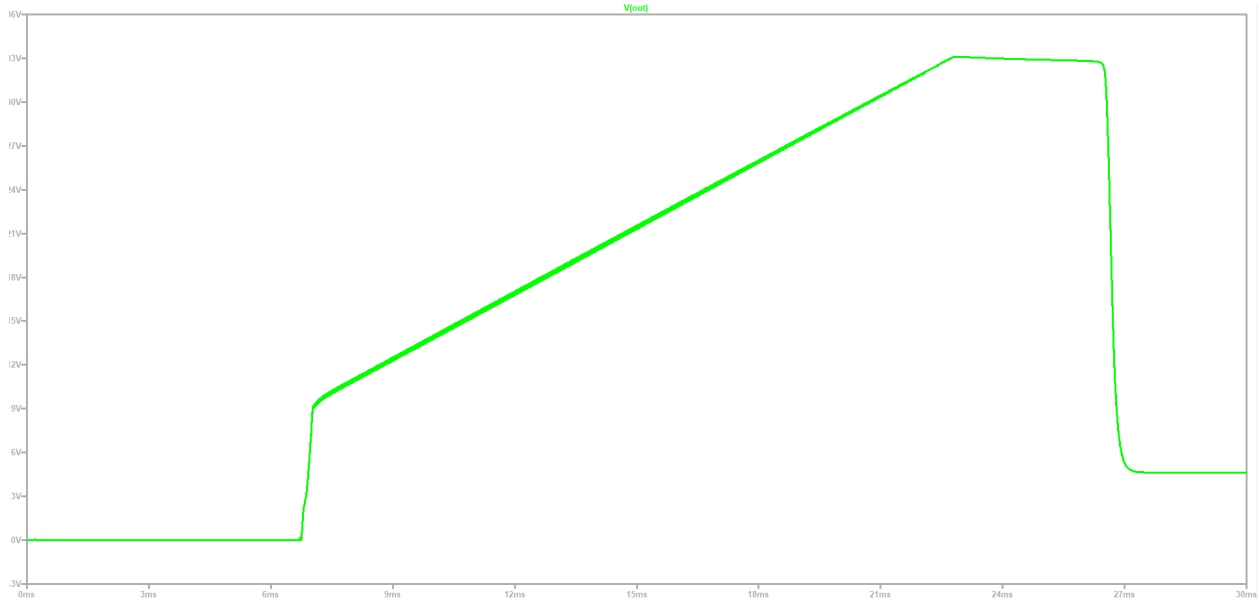
Figure 30: Simulation of the HEMT at 60 Volts input and 10 Ohm Load

As seen in *Figure 30*, the current design failed to meet the extreme requirement test of an input of 60 volts and a 10 Ω load, as the output voltage does not reach the 36-voltage requirement. The voltage dropped from 33 Volts to 5 Volts around 26.5ms. After about 3 weeks of simulating, Juan found that the inductor had a series equivalent resistance of 7 Ohms, leading to this simulation. Once fixing the ESR, the simulation at the higher voltage showed a stable 36 Volt output. *Figure 31* below shows the output voltage after fixing the ESR.
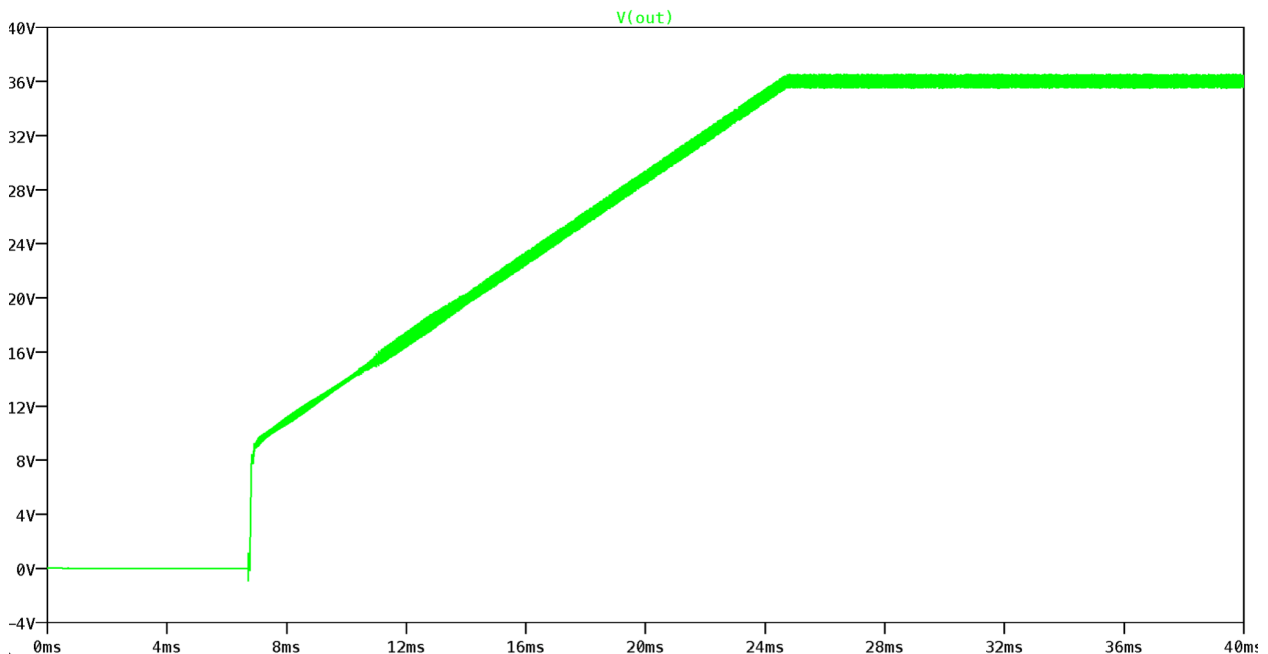
Figure 31: Simulation of the HEMT at 60 Volts input and 10 Ohm Load (Fixed ESR)

An .asc is provided below to those that wish to continue the project. The libraries and device models used are listed below at the bottom of the .asc.

```
/*GS66502B File used for simulation*/
C1 N012 0 .3µ Rser=3.54 Cpar=100p
C2 N013 N015 4.7n Cpar=100p
V1 IN 0 60
Rsense SW1 N003 4m
C3 N004 SW1 .1µ Rser=10.61 Cpar=100p
L1 N003 SW2 47µ Rser=7
RESR QD3 OUT 3m
C4 SW2 N005 .1µ Rser=10.61 Cpar=100p
Rt N014 0 309K
R3 OUT N009 175k
C5 N007 0 4.7µ Rser=0.23 Cpar=100p
C6 N010 0 .47µ Rser=2.26 Cpar=100p
XU1 QS2 N004 SW1 N001 SW1 N003 QD1 N007 N006 MP_01 N010 N010 N010 QD3 OUT N011
N008 N012 N009 N013 N014 0 NC_02 QD3 N002 SW2 N005 QS4 0 LT8390
R4 N009 0 5k
R6 N008 N007 100K
R2 N006 0 120k
R1 QD1 N006 363K
Rload OUT 0 10
C7 OUT 0 4.7µ Rser=0.23\ Cpar=100p
C8 QD1 0 2.5m Rser=12m Lser=0.68u
C9 QD3 0 4.7µ Rser=0.23 Cpar=100p
C10 QD3 0 1µ Rser=1.06 Cpar=100p
C11 QD1 0 1µ Rser=1.06 Cpar=100p
R5 QD1 IN 1
Rfilter N015 0 27k
XU3 QS4 SW2 0 EPC2012c
XU5 QS2 SW1 0 EPC2012c
XU6 N001 QD1 SW1 EPC2012c
XU7 N001 QD1 SW1 EPC2012c
XU2 N002 QD3 SW2 EPC2012c
XU4 QS4 SW2 0 EPC2012c
.tran 0 30m 0 200n startup

.lib EPCGanlibrary.lib
.lib LT8390.sub
.backanno
.end
```

/*GS66502B Model Provided by GaN Systems*/
* Created in LTspice Version XVII   *
*   *
* GaN Systems Inc. Power Transistors   *
* LTSpice Library for GaN Transistors   *
* Version 4.1   *
*   *
****
****
*   *
* Models provided by GaN Systems Inc. are not warranted by   *
* GaN Systems Inc. as   *
* fully representing all of the specifications and operating   *
* characteristics of the semiconductor product to which the   *
* model relates. The model describe the characteristics of a   *
* typical device.   *
* In all cases, the current data sheet information for a given *
* device is the final design guideline and the only actual   *
* performance specification.   *
* Altough models can be a useful tool in evaluating device   *
* performance, they cannot model exact device performance under *
* all conditions, nor are they intended to replace bread-   *
* boarding for final verification. GaN Systems Inc. therefore *
* does not assume any liability arising from their use.   *
* GaN Systems Inc. reserves the right to change models without *
* prior notice.   *
*   *
* This library contains models of the following GaN Systems   *
* Inc. transistors: *
*   *
*   GS66502B   *
****
*Level 1. Optimized for simulation speed.
*$
*$
.subckt GaN_LTspice_GS66502B_L1V4P1 gatein drainin sourcein source_S
*
*
.param sf = 0.225
.param rTC=-0.004 gan_res={40.7e-3}   metal_res={3.2e-3}   gtc=2.815 sh_s = 0.05263   sh_d = 0.94376
.param cur=.099 x0_0=1.1   x0_1=1.1 x0_2=1.0 thr = 1.61 itc=0.415 atc=98.33358
*
*

rd drainin drain { sh_d * (metal_res*(1-1*rTc*(Temp-25)) + gan_res*PWR((Temp+273)/298,gtc)) / sf }
rs sourcein source { sh_s * (metal_res*(1-1*rTc*(Temp-25)) + gan_res*PWR((Temp+273)/298,gtc)) / sf
}
RSS source_S source {0.001 * sf}
rg gatein gate {1.0 * sf}
*
*
Rcsdconv drain source {4000Meg}
Rcgsconv gate source {4000Meg}
Rcgdconv gate drain {4000Meg}
*
*
bswitch drain2 source2 I = (if(v(drain2,source2)>0,
+   (cur*(-(Temp-
25)*itc+atc)*log(1.0+exp(26*(v(gate,source2)-thr)))*
+   v(drain2,source2)/(1 +
max(x0_0+x0_1*(v(gate,source2)+x0_2),0.2)*v(drain2,source2))),
+   (-cur*(-(Temp-
25)*itc+atc)*log(1.0+exp(26*(v(gate,drain2)-thr)))*
+   v(source2, drain2)/(1 +
max(x0_0+x0_1*(v(gate,drain2)+x0_2),0.2)*v(source2,drain2))))) * sf
*
*
R_drain2 drain2 drain {(1e-4)}
R_source2 source2 source {(1e-4)}
*
*
C_GS   gate source   {263.3e-12 * sf}
C_GS1 gate source   Q = sf * (-0.9431e-12*(1-1./(1+exp(0.0177*(-v(drain, source)+300.03))))
+   -0.4182e-10*(1-1./(1+exp(0.0700*(-
v(drain, source)+33.3))))
+   -0.5657e-10*(1-1./(1+exp(0.277*(-
v(drain, source)+1.1))))
+   -(-0.435*90.48e-12*(1-
1./(1+exp(0.06*(-v(drain, source)+1.1))))
+   -0.435*0.54e-10*(1-1./(1+exp(0.9*(-v(drain, source)+2.1))))))))*x
C_GS2 gate source   Q = 0.464*2.23e-010*log(1+exp(6.5*(x-1.55))) * sf
*
*
C_GD   gate drain   {1.9e-012 * sf}
C_GD1   gate drain   Q = 0.444*4.6e-10*log(1+exp(0.277*(x+1.1))) * sf +
0.444*13.2e-10*log(1+exp(0.070*(x+33.3))) * sf + 0.444*1.2e-10*log(1+exp(0.0177*(x+300.03))) * sf
*
*

51

C_SD   source drain   {0.8e-010 * sf}
C_SD1 source drain   Q = 0.444*4.4e-9*log(1+exp(.15*(x+68))) * sf + 0.444*6.56e-9*log(1+exp(.03*(x+180))) * sf
*
*
.ends
*$