Spread Spectrum Buck Converter

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Abstract

Electromagnetic interference (EMI) is an issue prevalent to DC-DC converters. When a system doesn't effectively filter out external noise or signals, these signals can cause disturbances to the system at large. The switching technology of DC-DC converters (PWM in particular), lends the system susceptible to EMI because there is a prevalent peaks at the switching frequency, meaning any external signals will not be effectively attenuated at this frequency. This can cause significant issues at the input bus of the DC-DC converters because this bus is likely the input of a multitude of devices; the EMI susceptibility caused by switching technology makes the entire system vulnerable.

There are many proposed solutions to mitigate EMI, but our project focuses on spread spectrum frequency modulation (SSFM). SSFM is a way to utilize PWM technology by randomly varying the switching frequency within a set range of 10-20% centered at the desired average switching frequency; this served to eliminate harsh and potentially disastrous peaks at the switching frequency. Our project successfully implemented the spread spectrum technology of the LT8609 IC by using the IC in a 24/12V buck converter. We were able to clearly observe the frequency spectrum with the rectangular behavior characteristic of SSFM. The measured results were even better than the simulated results and our converter has made us confident in the viability of spread spectrum technology as a means to reduce EMI in DC-DC converters.

1

Introduction

1.1 Power Electronics Defined

Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches [1]. Power electronics range from the scale of milliwatts to gigawatts, lending them applicable to many systems. The applications of power electronics can be seen through all disciplines of electrical engineering, from solid-state physics to signal processing. Figure 1-1 displays a general array of the extent of power electronics.

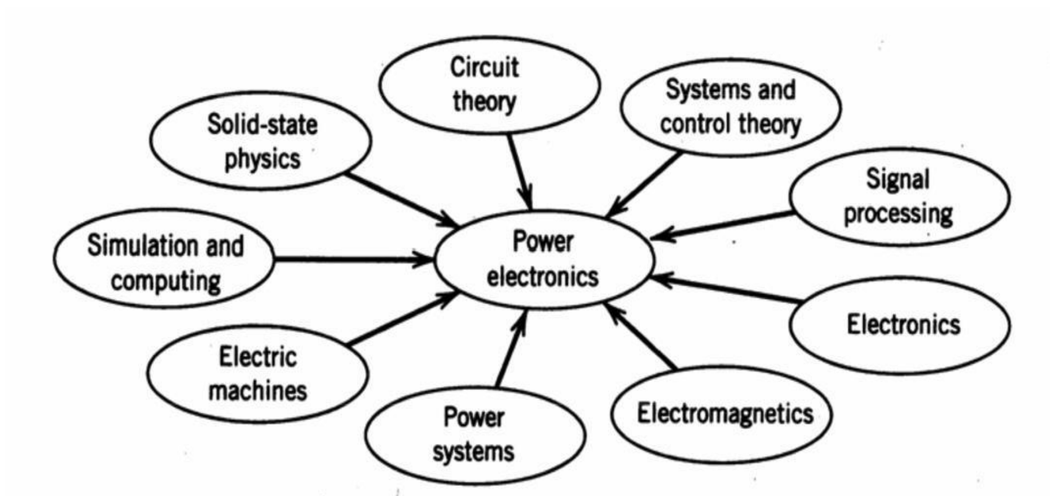

Figure 1-1: Interdisciplines Within Power Electronics

In today's market, power electronics seeks to reduce energy consumption to allow for more efficient designs; this increased efficiency is made all the more desirable in a world with a “need for carbon footprint reduction” [2]. They have the potential to improve conversion efficiency and generally have a “practically negligible” manufacturing cost in comparison to energy savings when introduced into existing systems [2]. Power electronics is a growing field due to the improvement in switching technologies and the desire for more efficient switching circuits.

1.2 Conventional Converters and Their Limitations

One method of power conversion is through the use of a linear regulator. A linear regulator steps down the input voltage to some desired output. The way a linear regulator achieves the conversion is by using a variable electronic device that creates a voltage drop. Even though a linear regulator is highly effective in maintaining the desired output this method is highly inefficient when the output to input voltage ratio is low due to significant series voltage drop which causes power dissipation in the regulator in the form of heat. Another limitation is the range of which the linear regulator can take. The input of the linear regulator needs to be close to the desired output for it to be efficient. If the input is not close enough the linear regulator could burn out because it will try to dissipate too much energy. Since majority of voltage converter applications required output voltage to be at a much lower level than the input; therefore, another and more robust method of energy conversion is needed for higher power converter applications.

Power converters are a valuable application of power electronics. The four main converter types are AC-AC, AC-DC, DC-AC, and DC-DC. DC-DC converters generally take a variable DC voltage and convert it to a fixed DC output voltage [3]. While the world is run by AC power, there are still many necessary DC applications today and thus the need for reliable devices to manipulate DC voltage in a cost effective way. There is a wide array of DC-DC converters such as buck, boost, buck-boost, Cuk, and Zeta [4]. Buck converters are a common topology that are used to step down a DC input voltage. The downside of buck converters, as with other DC-DC converters, is a susceptibility to electromagnetic interference (EMI) which can cause issues when the converter is implemented in a system [5]. However, there are a multitude of ways to lessen EMI and benefit from the "low power dissipation and high efficiency" buck converters have to offer [5].

1.3 Summary

Power electronics is an expanding field in electrical engineering because it uses switching technology to create efficient, low power systems. Different power electronic converters exist depending on the given input and desired output signal; DC-DC converters are one such power electronic device that manipulates DC power through many different setups such as buck or boost converter. Buck converters are widely used in consumer electronics to step down a DC input voltage such as from battery level to chip level DC voltages. However, just like in any other technologies, switching DC-DC converters such as Buck converter still have areas for improvement to enhance their performance. One example of commonly known issue is in terms of limiting EMI noise to maximize the practical applications of DC-DC converters.

2

Background

2.1 Problem To Be Solved

DC-DC converters are used in a wide range of applications. Buck converters in particular are a practical way to step down DC voltage without the use of a transformer. A common buck implementation uses pulse-width modulation (PWM) switching technique, in which there is a set switching frequency and the time-on is adjusted according to input from a feedback loop in order to regulate the output [6]. While effective, this method lends the system susceptible to electromagnetic interference (EMI) at the set switching frequency.

EMI results from quick current and voltage changes, which is the ideology behind “instantaneous” PWM switching [7]. This EMI can cause disruptions not only for the converter itself, but for any surrounding devices; EMI generated by PWM is not just a problem limited to the converter, but to the system at large. EMI noise travels along the power lines (conducted EMI), therefore any other device connected to the same power bus as the switch mode converter will be affected by the EMI noise. The power bus, typically a DC supply, can be spiked by the EMI noise and as a result the auxiliary devices might not tolerate the spike and be destroyed [8]. Another form of EMI is “radiated EMI”, which disturbs sensitive communication equipment. Due to the critical effects of EMI, electromagnetic compatibility standards have been created to mitigate EMI [8]. High switching frequency is desirable as it allows for smaller external components such as capacitors and inductors but this introduces EMI and greater power loss [9].

2.2 EMI Reduction Techniques

DC-DC converters come at a tradeoff, with “low power dissipation and high efficiency” but high susceptibility to EMI due to PWM technology creating a harmonic peak at the controller switching frequency [5]. There are several methods used to mitigate EMI and make DC-DC converters a more reliable power source for integrated circuits. Filtering, such as with ferrite beads, and shielding are common methods, but these methods come at the cost of lost space, weight, and a potentially large price tag [5].

Damping resistors are another proposed solution to EMI and while they may reduce EMI in the high frequency range, they increase EMI susceptibility in low frequency ranges [10]. Optimized PCB design can help reduce EMI to an extent by considering careful placement of the ground plane away from the switching plane, but this restricts PCB design [10]. However, a recent proposed solution to the DC-DC converters EMI issue is called spread spectrum frequency modulation (SSFM). PWM converters have a fixed switching frequency with a duty cycle that varies to generate the desired output. SSFM takes the idea of PWM and alters it so that the switching frequency is instead randomly varied within a range, centered around one frequency as seen in Figure 2-1. The idea of this random frequency is that instead of concentrating energy at one peak harmonic, the noise is distributed within a frequency band and there is an overall EMI reduction [11].

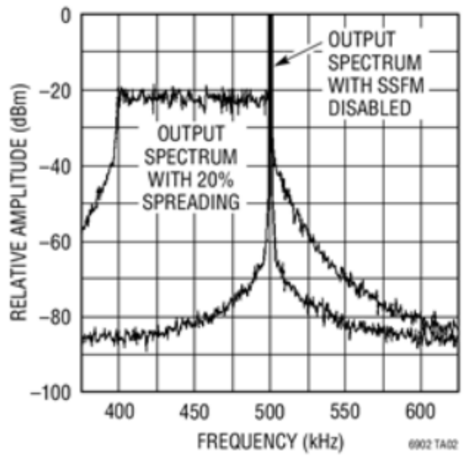

Figure 2-1: Frequency Display Showing Output Frequency Spectrum With and Without SSFM [8]

2.3 Spread Spectrum Technology Today

Spread spectrum is a technique that has become increasingly explored. For instance, it was implemented in a synchronous buck converter to explore the impact on higher order harmonics as SSFM to date has been primarily used to reduce the first harmonic EMI. This implementation observed that spread spectrum was effective in reducing conducted emissions and reduced emissions up to 5.7dB, with the peak emissions at the 97th harmonic [7].

Another study focused on using an FPGA controller with spread spectrum techniques to investigate consumer benefits. FPGAs are becoming increasingly popular because of their "higher performances in repetitive and massive computations;" combining FPGAs and DC-DC converters, which are necessary in many devices such as laptops and cell-phones and potentially become a direction the consumer market is taking [12]. The study found that with specific spread spectrum techniques (mainly the randomized frequency), noise was reduced at both high and low frequencies and the converter was able to operate as normal [12]. Essentially, spread spectrum is an effective way to reduce EMI, even with an FPGA controller, demonstrating that SSFM is a viable technique for the consumer market.

DC-DC converters that use PWM are a necessity in many areas of technology, from consumer products to high power operations. From these spread spectrum implementations it can be shown that SSFM is an effective technique for EMI reduction in DC converters.

2.4 Summary of Project

This project aims to utilize spread spectrum technology and demonstrate the potential benefits by showing the frequency spectrum of a buck converter with a spread spectrum chip. The LT8609 chip will be operated in spread spectrum mode and two buck converters will be built: a 24/15V and a 24/12V step down converter. The components of the converters will be chosen and the board will be laid out in Eagle to create a PCB. An open loop hall current sensor will also be implemented to observe the source current. In summary, this project will utilize a spread spectrum IC to investigate SSFM as a viable option for EMI reduction in practical buck operations.

3.1 Block Diagrams (Level 0 and Level 1)

At the simplest level, as seen in Figure 3-1, the system runs off of a 24V input and will output a 15V signal and a 12V signal alongside a reading of the input current. There will be valuable data to probe within the system; however, this block diagram illustrates the input and outputs broken down to the most basic form.

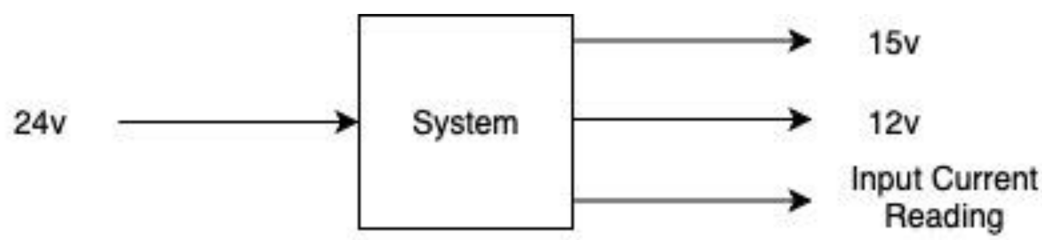

Figure 3-1: Level 0 Block Diagram

The level 1 block diagram, seen in Figure 3-2, elaborates on the inner workings of the system. The input voltage is stepped down to 15/12V using two LT8609 ICs, which are synchronous buck converters. The input current is measured using the ACS730, an open-loop hall current sensor whose output is then sent to an Arduino Uno to be displayed on an LCD screen after determining the proportional input current based on the output voltage of the current sensor.

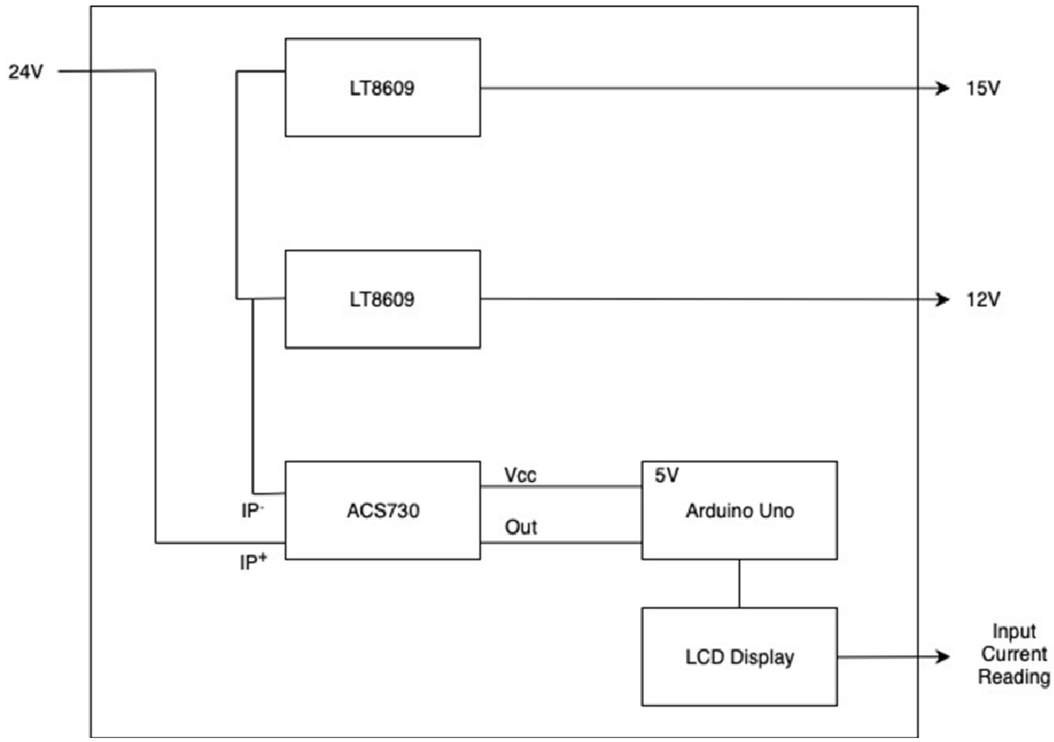

Figure 3-2: Level 1 Block Diagram

3.2 Technical Design Requirements

Input Voltage: 24V

The LT8609 converter is rated for a maximum of 42V. Ideally, the converter will be used in a standard DC system, so 24V and 48V are standard bus voltages. Since 48V is beyond the rating of the IC, 24V is a reasonable input that fits the specs of the board.

Output Voltages: 15V/12V

12V is a reasonable step down voltage and is also a common DC voltage used in systems. 15V is less common, but ideally we would like to observe the effects of spread spectrum at different duty cycles. The two converters will also be run off of the same bus to observe the effects of synchronizing the two ICs, specifically ICs with different outputs to see how well the LT8609 can operate from the same bus in spread spectrum mode.

Output Currents: 2A/1A

The 15V system will run at 2A, while the 12V system will run at 1A. The LT8609 is rated for an average current of 2A, with capability to handle 3A but not for extended periods of time. The different rated currents further serves to create two completely different systems that will be run off of the same bus.

Switching Frequency: 500kHz

Many standard PWM converters use a switching frequency of 500kHz because even if a system can use a higher switching frequency, the power loss is increased at higher frequencies. The LT8609 can use switching frequencies in the megahertz range, but since the input current will be sampled by a current sensor with a maximum sampling rate of 1MHz and we are investigating if spread spectrum can be a viable option in standard systems, 500kHz is a reasonable switching frequency to observe.

Inductor Ripple: Between 30% and 35%

While ideally a system will be as low efficiency as possible, we are investigating EMI of our system. The inductor ripple is ideally as low as 20% to increase efficiency, but this will make it much more difficult to observe the output EMI. Increasing the ripple will make the system more susceptible to EMI and we will be able to see the effects more clearly. 35% ripple is a cutoff that will allow our system to still be relatively efficient, but still show the effects of EMI.

Efficiency: 85% or above at full load

If this project was focused on designing a buck converter for actual implementation, the efficiency would ideally be above 90% at full load. However, since we are making sacrifices in efficiency (such as inductor current ripple), we have set 85% as a goal for full load condition.

Output Voltage Ripple: No more than 5%

A 5% voltage ripple is a reasonable standard to make sure the output voltage is as consistent as possible. There of course will be fluctuations, but minimizing these fluctuations in output voltage may help to get more accurate EMI results.

Load Regulation: No more than 3%

When varying the output current from 10% to 90% at the nominal input voltage, the load regulation should be no more than 3%. If the output voltage changes significantly because the load current changes, this could interfere with standard EMI results we hope to observe.

Line Regulation: No more than 3%

The input voltage should be varied from 20V to 28V while at full load current and the line regulation at these conditions should be no more than 3%. As with load regulation, in order to accurately observe the EMI just as a result of spread spectrum, the factor of a varying output causing a varied input should be avoided to more accurately observe the EMI at just one voltage.

3.3 Measurable Specifications

Electrical Specifications

As justified in Section 3.3, a summary of the electrical specifications of the system is as follows:

- 24V nominal input voltage ± 4V variation
- 15V/2A and 12V/1A outputs
- 500kHz switching frequency
- 30-35% Inductor Current Ripple
- Efficiency 85% or above at full load
- Output voltage ripple ≤ 5%
- Load regulation ≤ 3%
- Line regulation ≤ 3%

Physical Specifications

- PCB Dimensions: 3” x 4”

  This project will increase our knowledge of PCB design. Ideally, the board will be as compact as possible to still allow for practical power flow. A 3” x 4” PCB is a reasonable target for a compact board for this project that still gives us room to include a current sensor, two converters, and the additional feedback resistors and capacitors.

- Protected Final Package: 3D Printed Casing

  Time permitting, it would be practical to have the final product in a package. After designing the PCB, through SolidWorks we will design and 3D print either a packaged box with spaces for both the PCB and Arduino Uno, or just a casing for the PCB. By having such packaging, both PCB and Arduino will be protected from the outside environment as well as being safer when testing so that certain components are not touched.

3.4 Design Summary

The electrical and physical design specifications for the project can be seen and summarized in Table 3-1.

Table 3-1: Electrical and Physical Design Specifications

Nominal Input Voltage	24V
Nominal Output Voltages	15V/12V
Full Load Currents	2A/1A
Switching Frequency	500kHz
Inductor Current Ripple	30%-35%
Efficiency at Full Load	85%
Output Voltage Ripple	≤ 5%
Load Regulation	≤ 3%
Line Regulation	≤ 3%
PCB Size	3’’ x 4’’
Protected Package	Compact 3D Printed Case

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Design and Simulation Results

4.1 Solution Statement

The solution of this project is to reduce the susceptibility of electromagnetic interference in switch mode power supplies through the use of spread spectrum technology. The specific application which is being improved is the use of step down converters in the Cal Poly DC House. Conventional step down converters cause noise through EMI which affects other power converters connected to the same power bus or any other converter in series further down the line. Therefore, through the use of a synchronous spread spectrum converter, the amount of EMI emitted will be significantly reduced, which in turn improves the efficiency of other power electronic devices because the input of these devices will be much cleaner. The system under test will observe two step down converters run off of one voltage source to see the input current harmonics.

4.2 Component Selection

Our design was centered around the LT8609 synchronous step-down regulator. The datasheet and provided LTspice model of this IC provided a basis for component selection. Since the IC is a synchronous regulator, the switches of the converter are internal. Therefore the primary components our group had to decide on were the inductor, input capacitor, and output capacitor as well as the proper current sense to monitor the input current. Figure 4-1 shows the finalized circuit schematic.

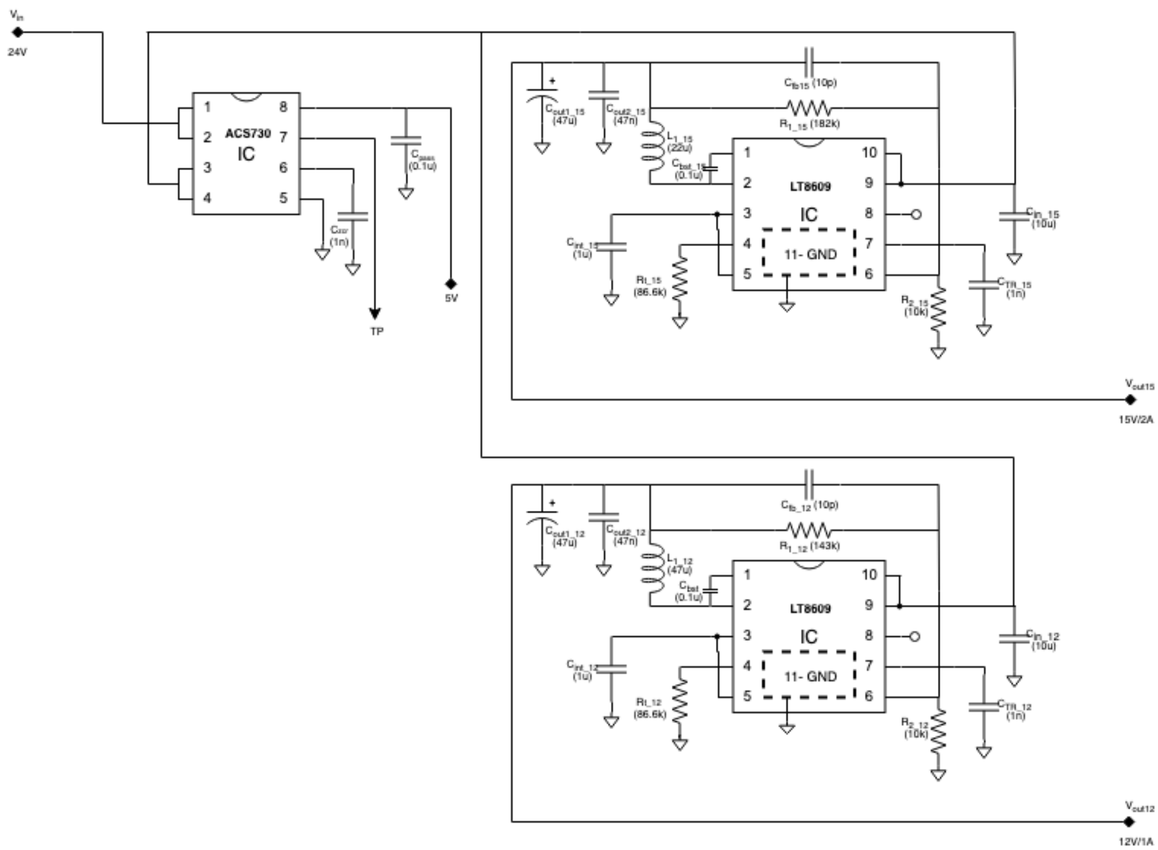


Figure 4-1: Circuit Schematic

Switching Frequency

The datasheet provided a table of resistors set at the R_T pin which sets the switching frequency of the PWM. The switching frequency was set to be 500kHz so that the current sensor could accurately and precisely monitor the output current of the PWM; the refresh rate of the current sensor is 1MHz. 500kHz is also a fairly standard PWM switching frequency.

Inductor Selection

The datasheet provided a starting value according to the equation

$$L = \frac{V_{out} + V_{sw(bot)}}{f_{sw}}$$

where $V_{SW(bot)}$ is approximately 0.25V and our selected switching frequency is 500kHz.

Table 4-1 shows the recommended starting values according to this equation for both the 15V and 12V output.

Table 4-1: Inductor Selection Results

	Recommended Inductor Value (μH)	Adjusted Inductor Value (μH)
15V Output	30.5	22
12V Output	24.5	47

While the datasheet provided a good basis of where to start for the inductors, we used the LTspice model to adjust the inductor value until I_{LPP} was at least 35% of the average output current. As explained in the previous chapter, this is to make sure that the output harmonics will be more easily seen. If the peak-to-peak current is too low or significantly filtered, it will be more difficult to observe the EMI results. In practical applications, this peak-to-peak should be lowered but for our specific tests a larger I_{LPP} was desired.

Input Capacitor

The input capacitor was determined based on the datasheet recommended value of **10uF**, with the capacitor being ceramic. Since the input current harmonics will also be observed, we did not need a large amount of input capacitance.

Output Capacitor

The starting value for the output capacitor was determined based on the equation:

$$C_{out} = \frac{100}{V_{out} * f_{sw}}$$

The recommended values based on this equation can be seen in Table 4-2.

Table 4-2: Output Capacitor Selection Results

	C_{out} Recommended Capacitor Value (μF)	C_{out} Adjusted Value (μF)
15V Output	13.333	47
12V Output	16.667	47

In order to decrease output current ripple as well as keep ESR low, we found a $47\mu F$ capacitor that had relatively low ESR. The capacitor has two essential functions which are to help filter the square wave generated and produce a DC output.

Alongside the primary electrolytic output capacitor, we added another small ceramic capacitor to reduce ESR. Electrolytic capacitors typically have a large series resistance while ceramic capacitors have a low series resistance, so adding a ceramic capacitor in parallel is desired to lower ESR. A 47nF ceramic capacitor was chosen.

Feedback Resistor Network

The datasheet provided a starting value according to the equation

$$R_1 = R_2(\frac{V_{out}}{0.782} - 1)$$

The feedback resistor network is a voltage divider which functions to set the output voltage. It also serves to act as a small load on the output which optimizes the quiescent current at low loads. The 10pF capacitor is inserted within the network to act as a phase lead compensator. R2 was selected to be 10kΩ so that the voltage divider network would consume minimal power while drawing little current. The finalized values can be seen in Table 4-3.

Table 4-3: Feedback Resistor Selection Results

	R1 ($k\Omega$)	R2 ($k\Omega$)
15V Output	182	10
12V Output	143	10

Current Sensor Selection

In selecting a current sensor, we determined an open-loop hall current sensor was ideal because it isolates the current sense circuit from the circuit being measured. From there, the **ACS730** was chosen because of its compact size and its large current rating (30A) as well as its fast sampling speed of 1MHz.

4.3 Simulation Results

The LTspice model for the LT8609 IC was provided so both the 15V and 12V step down converters were modelled. Figure 4-2 displays the finalized LTspice circuit schematic.

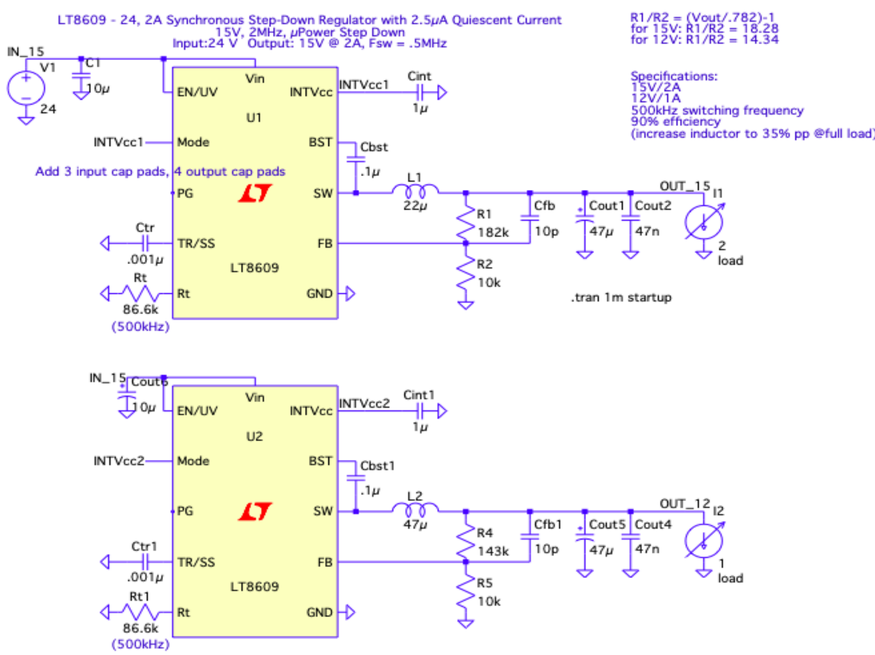


Figure 4-2: LTspice Circuit Schematic Neglecting the Current Sensor

There were several tests performed using the LTspice schematic. For purposes of the tests the ICs were synchronized by tying together their "Sync" pins, which sets them to the same internal clock pulse; it should be noted that when they are not tied together they still run at nearly the same pulse since there is no delay on either of the clocks, so they are naturally "synchronized" through simulation.

The first test was to verify that the outputs were correct. Figure 4-3 displays the output current, output voltage, and output power for the outputs. Data from these outputs such as time to steady state can be seen summarized in Table 4-4.

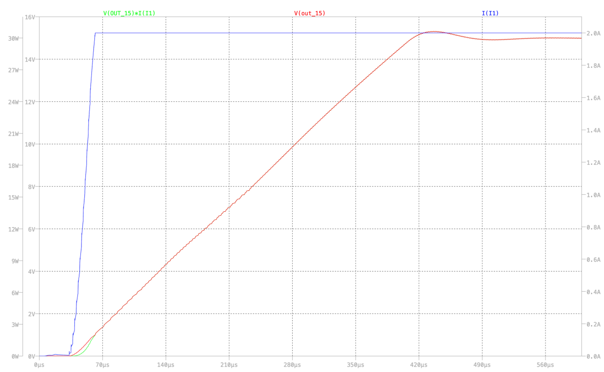


Figure 4-3a. Voltage, Power, and Current of 15V Converter

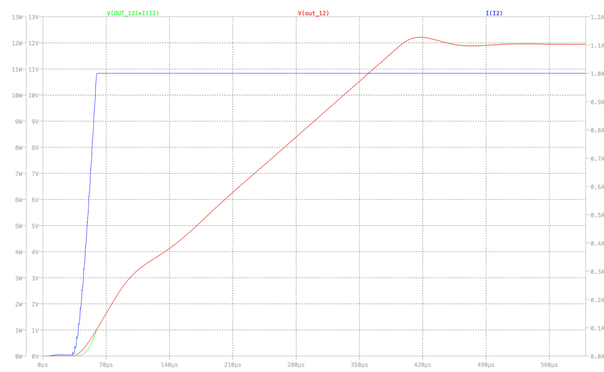


Figure 4-3b. Voltage, Power, and Current of 12V Converter

Table 4-4: Data Summary of 15V and 12V Converter Outputs

	Time to Steady State (μs)	Voltage (V)	Current (A)	Power (W)
15V Output	560	15	2	30 ± 0.04
12V Output	530	12	1	11.95 ± 0.02

After confirming the outputs were confirmed to be correct, the input current and output current harmonics were tested using the Gaussian FFT function in LTspice. Theoretically, spread spectrum should eliminate a peak at the switching frequency and instead show a rectangular-shape at lower magnitude.

Figure 4-4 display the input current harmonics which is the most important FFT since the source will be supplying other power electronic devices and must have low EMI susceptibility. As shown in the waveform, there is a rectangular behavior in the 500kHz range as expected instead of a larger peak at 500kHz.

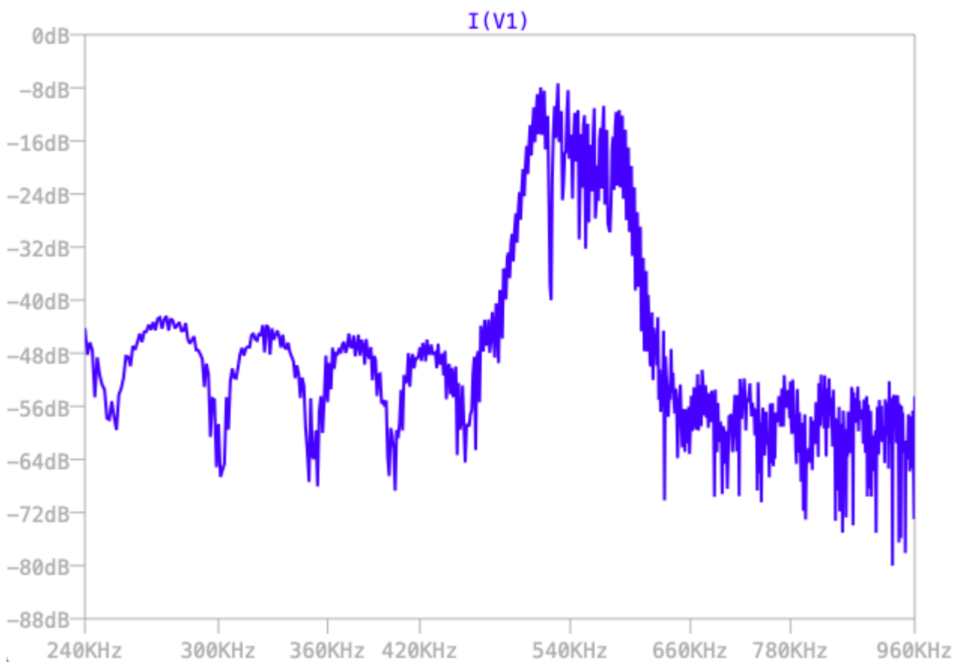


Figure 4-4: Input Current FFT in 500kHz Range

The output current FFT was also observed for the 15V and 12V outputs. Figure 4-5 shows the resulting harmonics, but as seen in the figure the harmonics are in the -60dB range, so the input current harmonics are the more concerning factor.

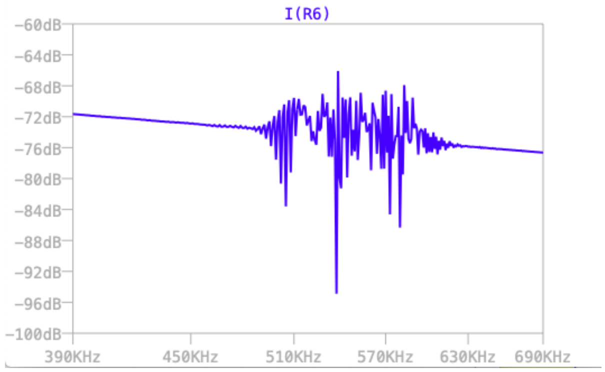


Figure 4-5a. 15V Converter Output Current FFT

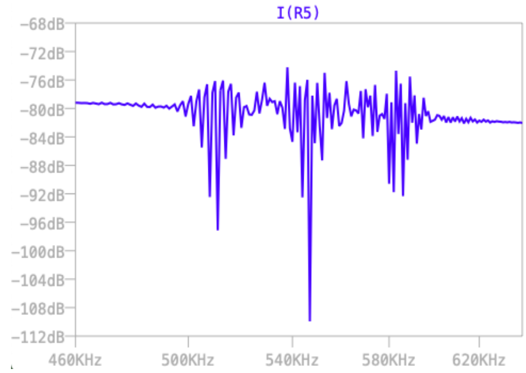


Figure 4-5b. 12V Converter Output Current FFT

4.4 Summary

In order to test the functionality of spread spectrum technology in PWM applications, our project uses a step down converter in spread spectrum mode; theoretically the input current harmonics will be less focused at a peak at the switching frequency and instead will be averaged out around the switching frequency. Using the provided LTspice model for the chosen LT8609 IC as well as the datasheet recommendations, we have designed a circuit to observe input current harmonics when one source powers two converters.

5

Hardware Test and Results

5.1 Hardware Procedure

Our proposed converter design was physically assembled using a PCB. EAGLE was used to design the board and the board was then printed by OSH Park. Figure 5-1a. shows the finalized PCB design in EAGLE and Figure 5-1b. shows the PCB we received.

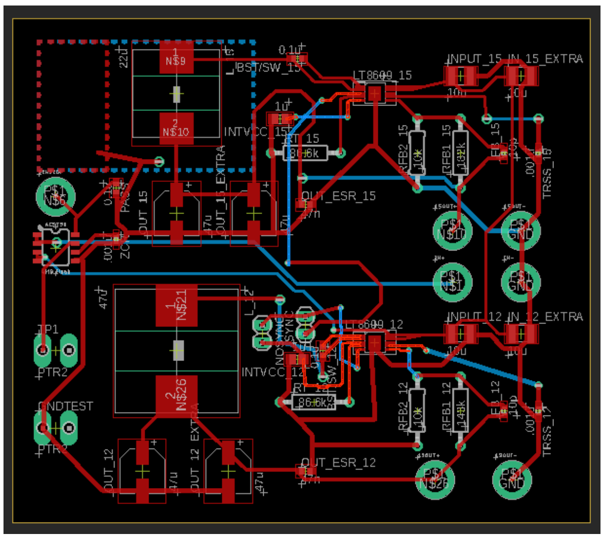


Figure 5-1a. EAGLE PCB Design (Board 1)

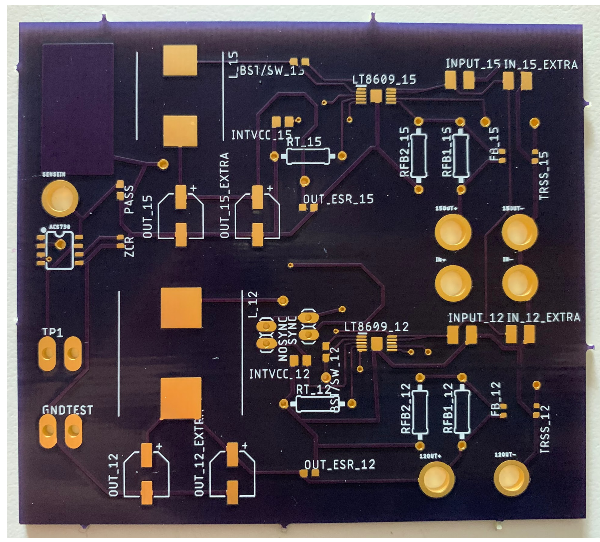


Figure 5-1b. Resulting EAGLE PCB

After receiving the board, all of the components had to be soldered. Jaime Carmo used hot air to solder the LT8609 IC as it was an incredibly small package with a ground plane on the bottom; our group then soldered the rest of the components. One issue that came up was that the female-banana plug-ins did not fit the holes on the board, so instead 26 gauge wire was used to create “hooks” for banana-grabber connections. Figure 5-2 displays the board with all of the components successfully soldered.

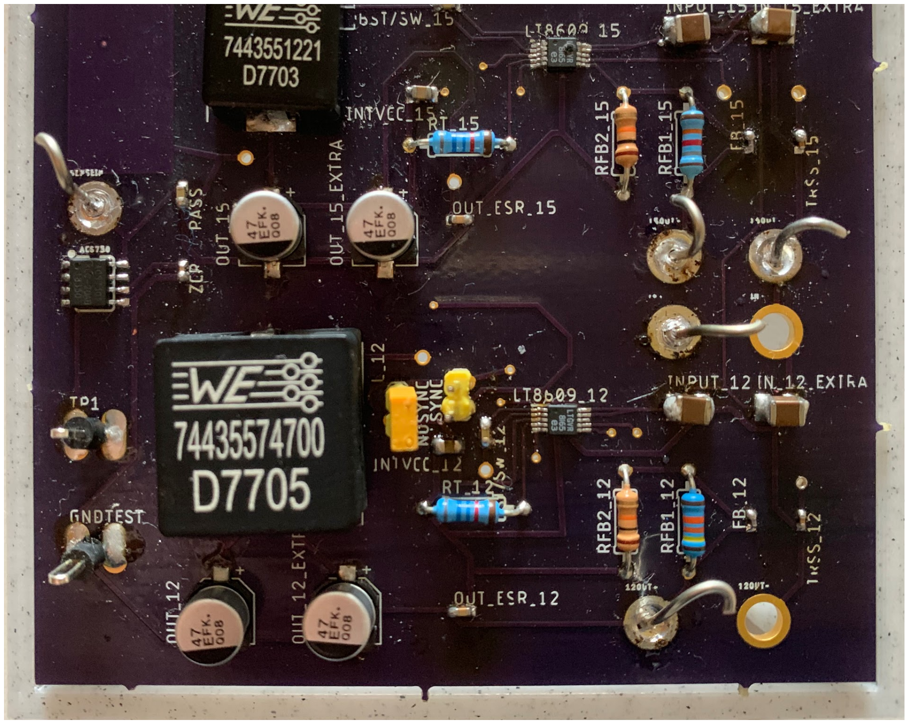


Figure 5-2: Completely Soldered PCB

At the same time as testing our first board, another board was designed in EAGLE. This new design had just one converter, however the resistor that sets the switching frequency was replaced with a potentiometer so we could observe the effects of an altered switching frequency on the input harmonics. The board design was also improved so that the power flow was more linear and the ground plane was expanded. Figure 5-3a. shows the EAGLE PCB design while Figure 5-3b. displays the board we received from JLCPCB.

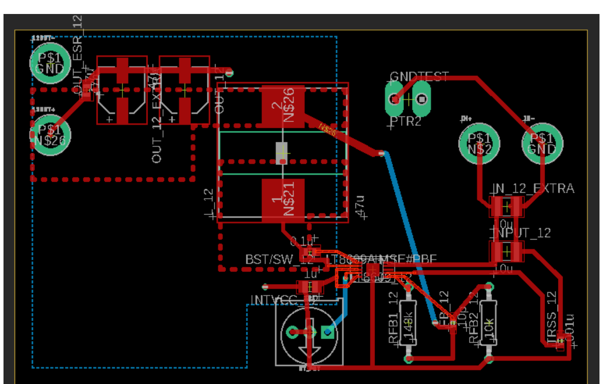
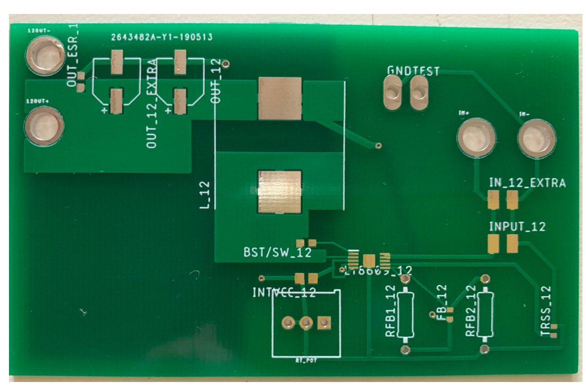


Figure 5-3a. EAGLE PCB Design (Board 2)



5-3b. Resulting EAGLE PCB

The new board was soldered using hot air for all surface mount component and a soldering iron was used for all through hole components. There were two assembled because the first attempt had immediate failure due to poor soldering connection of the integrated circuit. Figure 5-4a is the first attempt while the figure 5-4b is the more successful one.

Figure 5-4a: Attempt 1

Figure 5-4b: Attempt 2

The completed board in figure 5-4b has a resistor soldered in place of the potentiometer because the desired resistance is 86.6 kΩ while the potentiometer max value is 10 kΩ. The potentiometer would set the switching frequency over 2.2 MHz.

5.2 Testing- Load Regulation, Line Regulation, Efficiency

The first test performed was an open-load test at nominal input voltage to confirm that the output voltage of each converter was correct. Table 5-1 shows the results of this first open-load test at a 24V input. This open-load test proved successful, but problems arose immediately with the first version 15V converter and the second version 12V converter had a load attached.

Table 5-1: Open-Load Voltage Test Results

	Open-Load Voltage (V)
Version 1	
15V Converter	15.22
12V Converter	12.12
Version 2	
12V Converter	11.89

Figure 5-4 shows the test set-up used to find load regulation, line regulation, and efficiency; the output voltage was measured using the multimeter rather than the DC load. Unfortunately, when testing version 1, as soon as we attached a load to the 15V converter (at around 0.1A) the converter cut-off, with voltage immediately dropping and the inductor making a lot of noise. We believe that there was a problem with sizing the inductor because the design for the 15V and 12V are extremely similar but the 12V converter has a larger inductor. Unfortunately, in trying to troubleshoot this converter, two pins on the LT8609 IC for the 15V converter were shorted when trying to probe pins and the IC was blown, lending the converter useless. The 12V converter still works, so all of the tests were done on the 12V converter only.

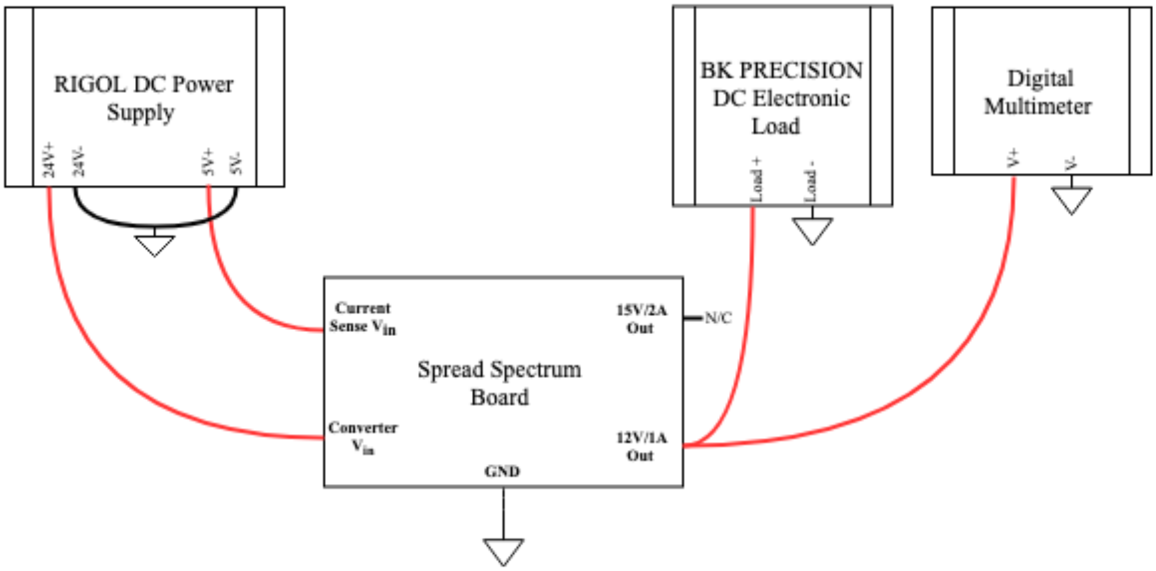


Figure 5-4: Test Setup to Measure Load Regulation, Line Regulation, and Efficiency

As for the second version, the converter was experiencing similar problems as the 15V circuit in version 1. At no load, the converter provided an output of 11.89V, which is sign of a poor converter because it would be more desired that the output is higher than nominal because the output tends to sag, therefore it was apparent that this converter was going to have poor load regulation. To aide the poor voltage output, capacitors were placed on the input and output of the converter. Unfortunately, one of the capacitors placed on the inputs were not rated for 24V, which cause it to melt and short the input of our converter. Thereafter, the second version no longer worked. The following testing is was done with the 12V circuit of our first version.

Load Regulation:

To measure load regulation, the following equation was used:

$$\text{Load Regulation} = \frac{V_{o(low\ load)} - V_{o(high\ load)}}{V_{o(high\ load)}} * 100$$

Table 5-2 shows the measurements taken to calculate load regulation and the finalized load regulation. Note these measurements were taken at the nominal input voltage of 24V.

Table 5-2: Load Regulation Measurements

$V_{O(LOW)} = V_{O(0.1A)}$	$V_{O(HIGH)} = V_{O(0.9A)}$	Load Regulation
12.053 V	12.046 V	0.058%

Line Regulation:

To measure line regulation, the following equation was used:

$$\text{Line Regulation} = \frac{V_{o(high\ input)} - V_{o(low\ input)}}{V_{o(nominal\ input)}} * 100$$

Table 5-3 shows the measurements taken to calculate line regulation and the finalized load regulation. Note that these measurements were taken at full load current of 1A.

Table 5-3: Line Regulation Measurements

$\mathbf{V_{O(HIGH\ IN)} = V_{O(28V)}}$	$\mathbf{V_{O(LOW\ IN)} = V_{O(20V)}}$	$\mathbf{V_{O(NOM\ IN)} = V_{O(24V)}}$	**Line Regulation**
12.058 V	12.075 V	12.055 V	-0.141%

Efficiency:

With the line regulation and load regulation exceeding expectations, the efficiency was then measured at nominal input voltage. The RIGOL power supply showed input power while the DC supply showed output current and the multimeter showed output voltage in order to get output power and then efficiency P_{out}/P_{in}. Figure 5-5 shows the resulting efficiency versus load current. The resulting efficiency exceeded expectations of 85% at full load.

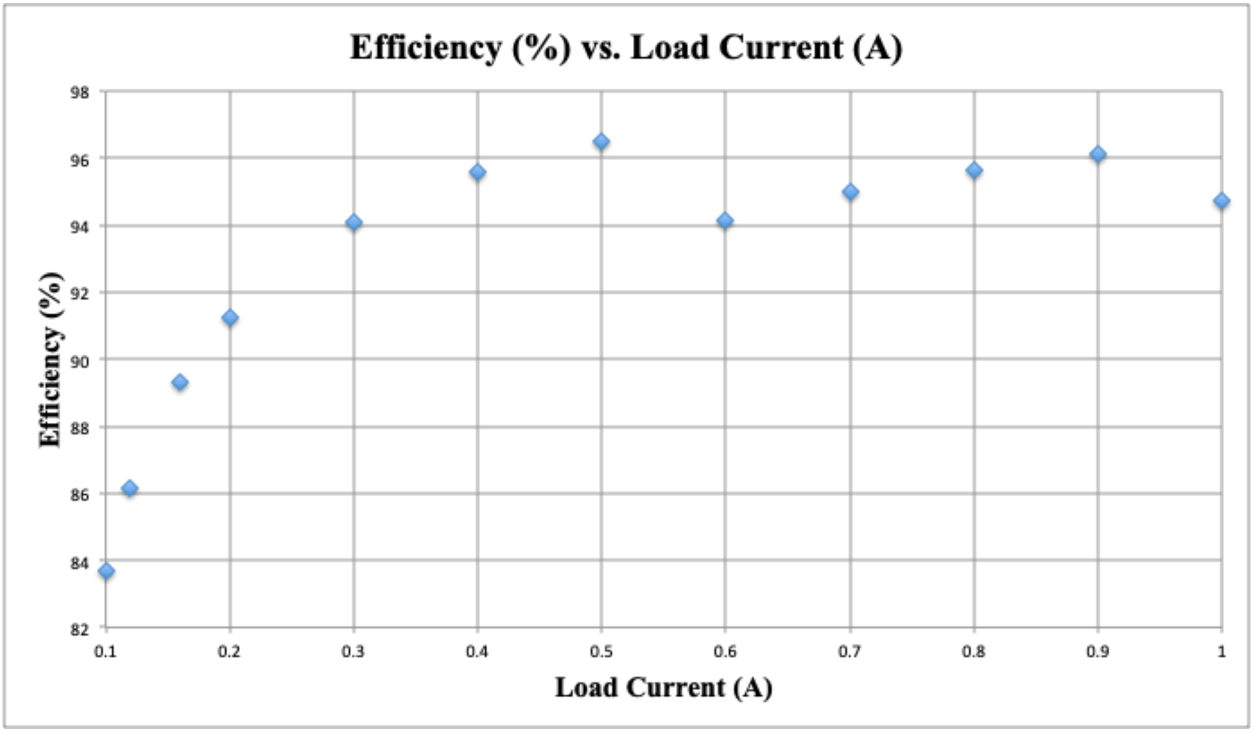


Figure 5-5: Efficiency (%) vs. Load Current (A)

5.3 Test Setup- Frequency Spectrum, Output Ripple, Inductor Current

Frequency Spectrum:

To observe the spread spectrum at work, the frequency spectrum had to be observed. The test setup can be observed in Figure 5-6; the scope probe measured the voltage at the side of the resistor not attached to 24V because that voltage measures the fluctuations in input current and therefore the FFT. At first a 100 MHz oscilloscope was used to observe the FFT. However, this was not an accurate way to observe the spectrum around 500 kHz so the HDO4104, which is a 2.5 GHz oscilloscope, was used instead. Originally the ACS730 current sensor was going to be used to observe the FFT, but a current sense resistor was used instead because the sampling rate of the ACS730 was not fast enough to yield effective results.

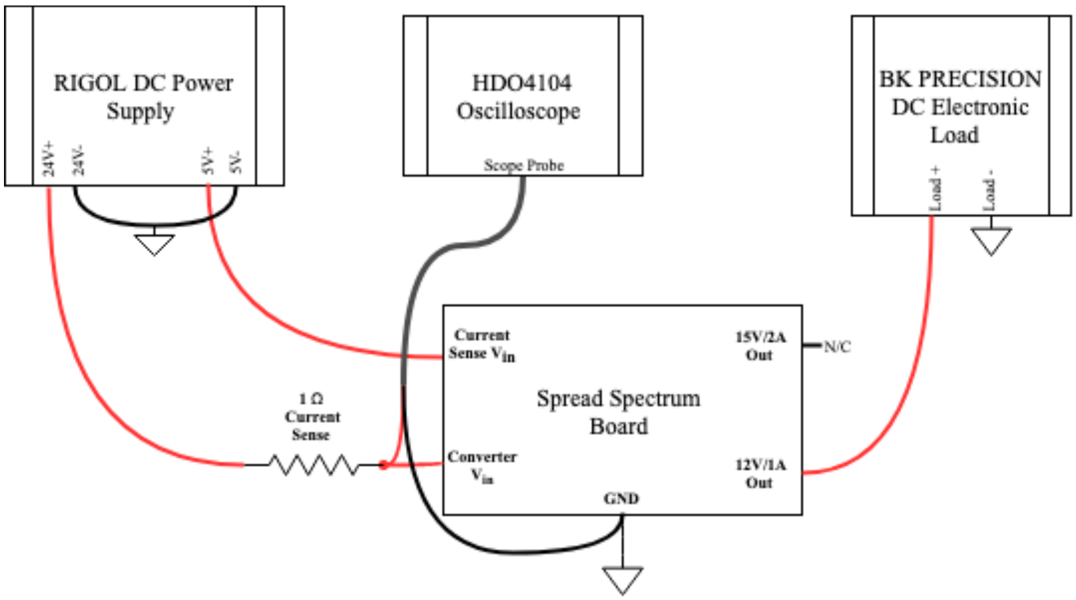


Figure 5-6: Test Setup to Measure FFT of Input Current

The data was exported to excel and plotted as seen in Figure 5-7. It shows an extended spectrum with a distinct peak around 520,000 kHz. However, when the spectrum is zoomed in as in Figure 5-8, it is easier to see the distinct rectangular behavior that is associated with spread spectrum. Several distinct points are summarized in Table 5-5. The behavior is consistent with our expectations as we chose 500 kHz as the bottom limit of our frequency spectrum so it will randomly switch between the chosen frequency and +10%, so between 500 kHz and 550,000 kHz.

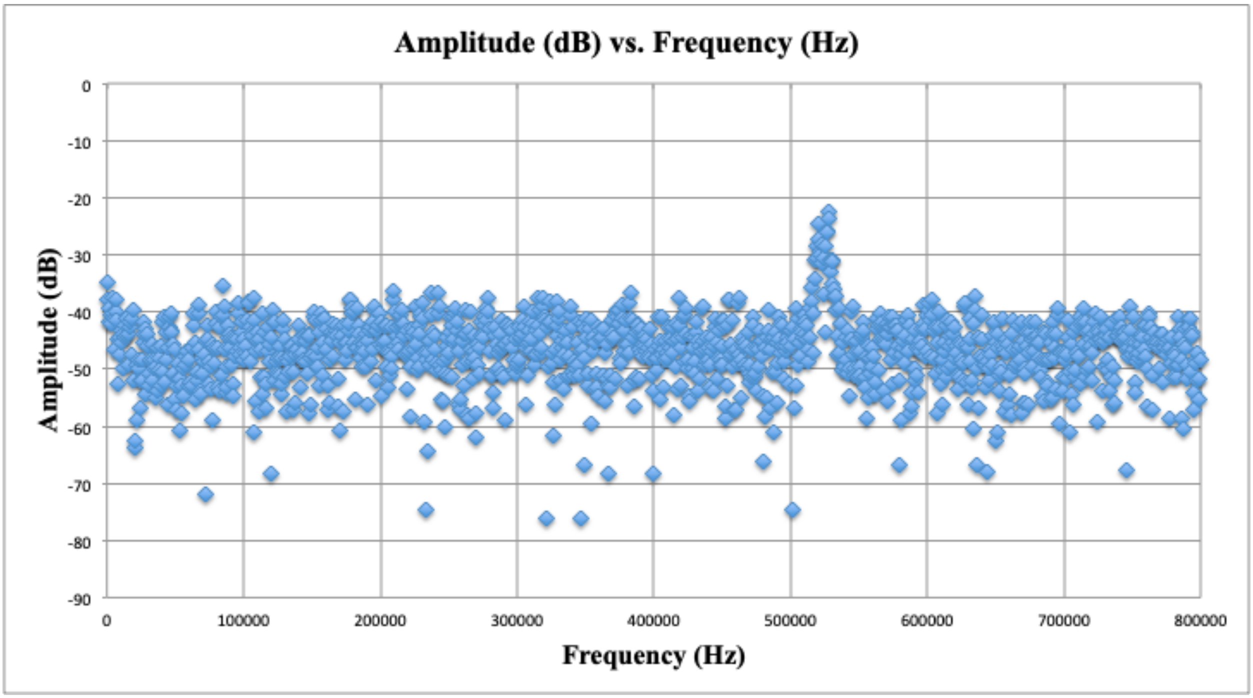


Figure 5-7: Input Harmonic FFT from 0 to 800,000 kHz with Distinct Peak Around 520 kHz

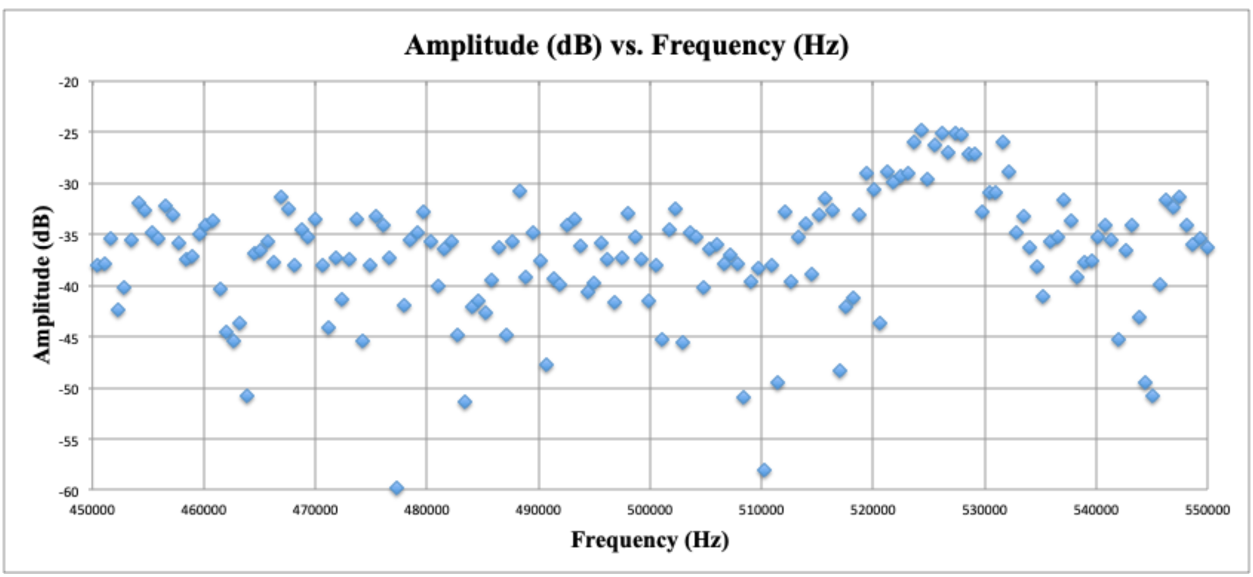


Figure 5-8: Input Harmonic FFT with Rectangular Behavior Around 520,000 kHz

Table 5-4: Key Points from FFT

Title	Frequency (kHz)	Amplitude (dB)	Explanation
Peak Harmonic	527.3	-25.023	This is where the worst-case amplitude occurs, with a voltage of 0.053 occurs
Beginning of Rectangular Peaking	510.0	-38.049	This is the point where the amplitude starts to increase, as the rectangular behavior begins
End of Rectangular Peaking	540.0	-35.183	This is the point where amplitude decreases again and spread spectrum behavior is over

The test results of the spread spectrum follow a similar rectangular behavior as the following LTSpice simulation of our 12V converter in Figure 5-9, with cursor data seen in Figure 5-10. The critical points of this simulation can be seen in Table 5-5.

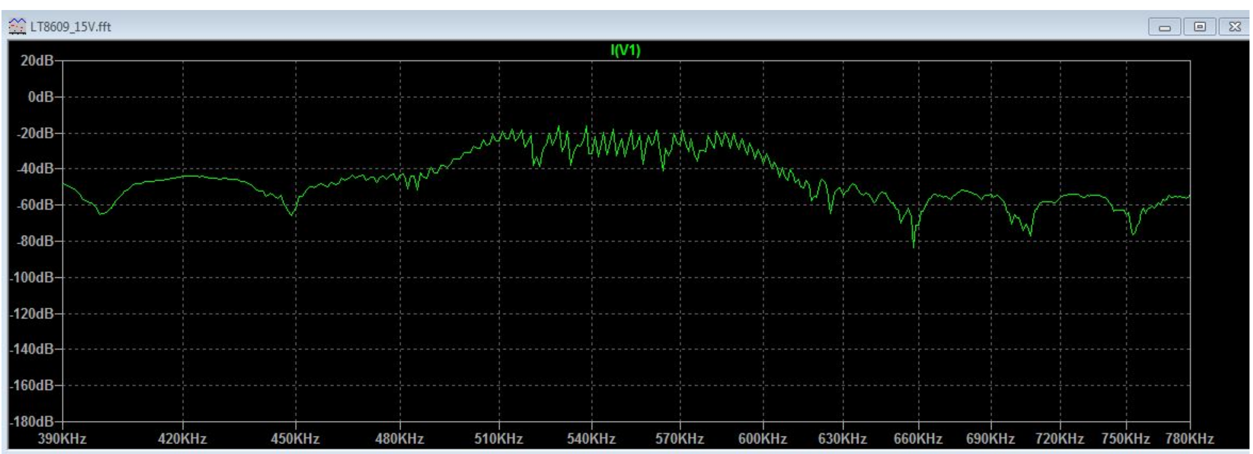


Figure 5-9: LTSpice Simulation with Spread Spectrum

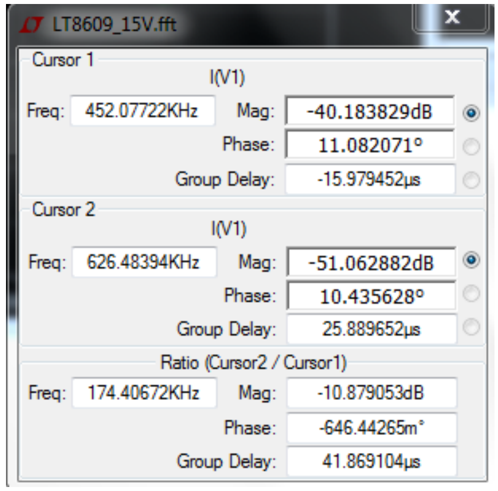


Figure 5-10: Cursor Data from Spread Spectrum Simulation

Table 5-5: Key Points from FFT Simulation in Spread Spectrum Mode

Title	Frequency (kHz)	Amplitude (dB)	Explanation
Peak Harmonic	583.9	-14.44	This is where the worst-case amplitude occurs, with a voltage of 0.053 occurs
Beginning of Rectangular Peaking	452.1	-40.18	This is the point where the amplitude starts to increase, as the rectangular behavior begins
End of Rectangular Peaking	626.5	-51.06	This is the point where amplitude decreases again and spread spectrum behavior is over

The measured results are indicative of the spread spectrum because the resulting FFT shows the magnitude distributed among a larger frequency span as is consistent with the simulation. The larger frequency span results in a reduced peak EMI.

Another comparison to be made through simulation is if the IC was not operated in spread spectrum mode. Figure 5-11 shows the FFT when it is not operated in spread spectrum, and there is a significant peak at 500 kHz. This peak is -7.15 dB, as compared to the -14.44 dB peak from spread spectrum.

Figure 5-11: LTSpice Simulation without Spread Spectrum

From this comparison it is clear why spread spectrum is useful, with a reduced peak amplitude. Unfortunately, the board was designed to only be operated in spread spectrum so we could not observe the circuit operating without spread spectrum, but it is safe to assume that the peak would be more significant and greater in amplitude without spread spectrum mode.

Output Voltage Ripple:

With the same oscilloscope and similar test setup as seen in Figure 5-6 (neglecting the current sensor), the output voltage ripple was measured. The scope probe was used to measure the 12V output. Figure 5-12 shows the data that was exported from the oscilloscope. There is significant noise and peak voltage at the points where the square switching wave is rising or falling. Table 5-6 shows both the peak-to-peak ripple from the switching, as well as the average peak-to-peak. In terms of comparing design standards, the average peak-to-peak was used because voltage peaks from switching is inherent to PWM designs. The average ripple voltage of 2.5% is within design standards.

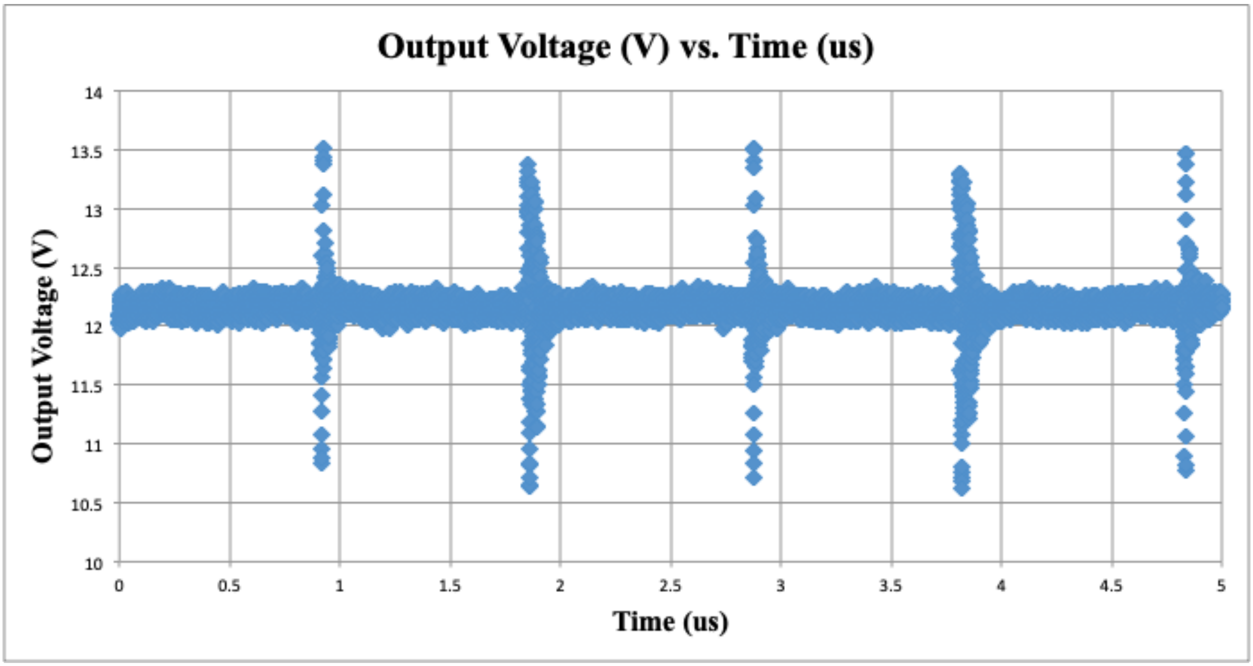


Figure 5-12: Output Voltage Ripple

Table 5-6: Output Voltage Ripple- Switching and Average

	Ripple Voltage (V)	**Ripple %**
Switching	2.75	22.9
Average	0.30	2.5

Inductor Current:

With a similar test setup as seen in Figure 5-6 (neglecting the current sensing resistor) the inductor current was analyzed. In our PCB design we neglected to include a current sense resistor to monitor the inductor current, so in order to estimate the peak-to-peak inductor current, we observed the switching waveform and used the following equation:

$$V_L = L\frac{\Delta I_L}{\Delta t} \rightarrow \Delta I_L = \frac{V_L \Delta t}{L}$$

The logic was that one side of the inductor is tied to the switching voltage and the other is tied to a relatively constant 12V with slight ripple. The switching waveform was recorded as seen in Figure 5-13.

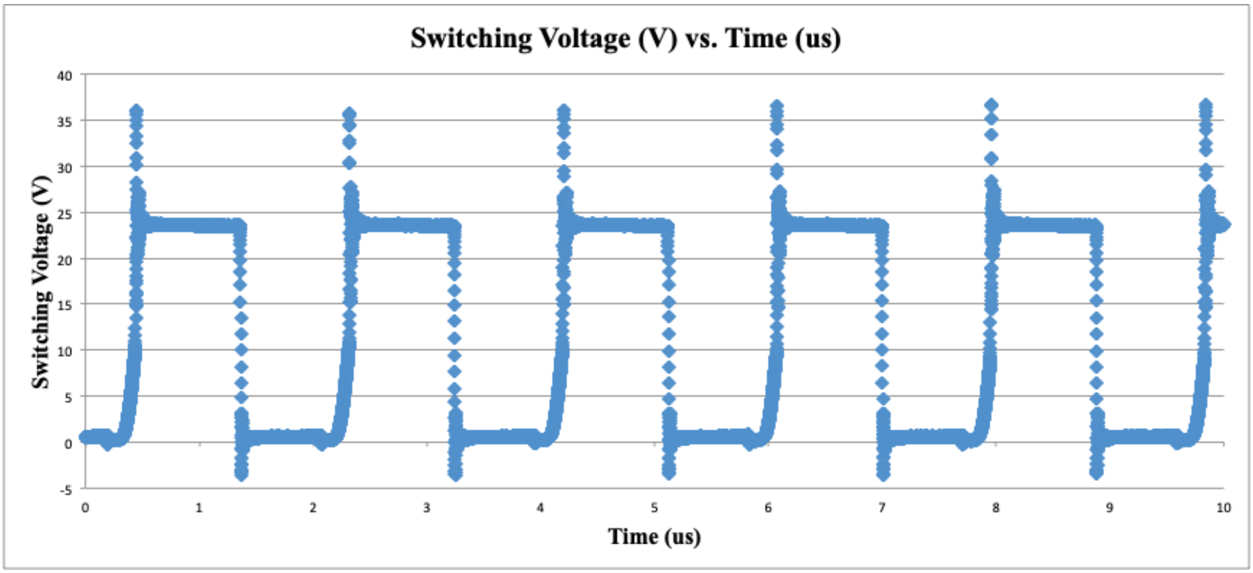


Figure 5-13: Switching Waveform Tied to First Side of Inductor

With this switching waveform and the logic of $V_L = V_{switching} - V_{out}$, where V_{out} is a constant 12V, the inductor ripple was determined through the following analysis (results summarized in Table 5-7):

Average switching voltage = 24V

D = 0.5

$V_{Lon} = 12V$

$V_{Loff} = -12V$

$\Delta t_{on} = \Delta t_{off} = 1\mu s$

$L = 47\mu H$

$$\Delta i_L = \frac{12V * 1\mu s}{47uH} = \mathbf{0.2553\ A}$$

Table 5-7: Inductor Current Ripple Summary

	Total Inductor Ripple (A)	**Inductor Ripple %**
Δ□□**(full load conditions)**	0.2553	25.53

The inductor current ripple was supposed to be rather large to help with viewing the frequency spectrum. However, this smaller inductor ripple is more desirable in actual practice so it is ok that the inductor ripple does not meet the original design standard.

5.4 Results Compared to Design Specifications

The measured values could be directly compared to the design specifications that were determined in a previous chapter. Table 5-8 shows the test results compared to these design standards; aside from inductor current ripple, which in practice gave a more desirable value but is not in the specified range, all the other measurements met the design specification.

Table 5-8: Resulting Measurements as Compared to Design Specifications

Design Requirement	**Measured Value**	**Design Specification**	**Comparison**
Load Regulation	0.058%	No greater than 3%	Exceeds design standards
Line Regulation	-0.141%	No greater than 3%	Exceeds design standards
Efficiency at Full Load	94.75%	Greater than 85%	Meets design standards
Output Voltage Ripple	2.5%	Less than or equal to 5%	Meets design standards
Output Current Ripple	25.53%	30-35%	Does not meet design standards
PCB Size	2.9” x 3.4”	3’’ x 4’’	Meets design standards

As can be seen from Table 5-6 the measured values met the design specifications in most regards. The improper behavior of the 15V converter could not be rectified and was chosen to be passed on for the time being.

5.4 Testing Summary

The tests of the 12V converter have proven to be successful compared to the guidelines previously set. The 12V converter operates beyond the efficiency, load/line regulation, and peak-to-peak output voltage design standards. The resulting FFT performed better than the simulation, with the largest amplitude being -25 dB. The new PCB is in the process of being soldered and we hope to find a way to operate that PCB in spread spectrum and then normally to compare the FFT and see if spread spectrum is a practical solution for EMI reduction.

Chapter 6

Conclusion

6.1 Original Problem

We sought to find if spread spectrum technology could be used as an effective means of reducing EMI within practical buck operations. EMI is a problem that exists within all electrical devices and solutions are consistently being sought out. EMI can be disastrous to the operation of neighboring components and even separate circuits. Within a buck converter the switching action associated with the switching frequency is the primary source of EMI. The noise created by the switching action affects other power converters connected to the same power bus or any other circuits/converter further down the line.

Spread spectrum frequency modulation is an effective method of "spreading" out a signal with a high peak, specifically the peak at the switching frequency of the input current harmonics. Therefore, through the use of a synchronous spread spectrum converter, the amount of EMI emitted will be significantly reduced. This in turn improves the efficiency of other devices on the same bus because the input of these devices will be much cleaner with less interference near the chosen switching frequency.

6.2 Our Project Expectations

We aimed to create two buck converters which stepped down a single 24V/3A supply into a 15V/2A and 12V/1A while operating at a switching frequency of 500kHz. The chip utilized is an LT8609 IC operated in spread spectrum mode. An open loop hall current sensor was placed at the input of the board to monitor the source current. The two step down converters designed are meant to be fitted into the Cal Poly DC house. Since the switching frequency of the converter is at 500kHz we expected that a high amount of noise will appear around that frequency. However the SSFM will cause the input current harmonics to be less focused at the switching frequency of 500kHz and be averaged around the switching frequency. By utilizing spread spectrum we believed that the input current harmonics at that frequency would be reduced due to "spreading" out the switching frequency, with a high dB peak, across a small range of frequencies centered around 500kHz. With a wider range but lower peak, less noise will be amplified and EMI will be reduced on the input side.

6.3 Results

The scope of the project is to utilize spread spectrum technology and demonstrate the potential benefits by observing the spectrum of a buck converter. The objective was to construct two boards, one with a 15V and a 12V circuits, which operate using SSFM. These two circuits were constructed on a single PCB board in spread spectrum mode. Unfortunately the 15V circuit did not work, but the 12V circuit was able to give the desired results. The input spectrum of the 12V circuit, which clearly demonstrate the effects of the spread spectrum method, can be found in Figure 6-1.

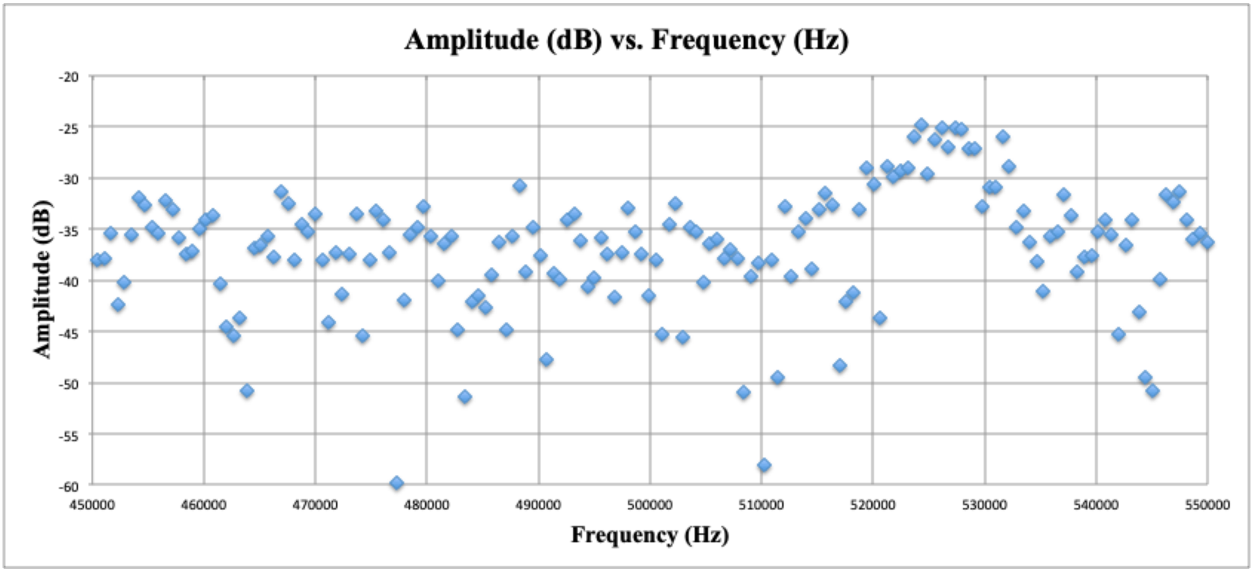


Figure 6-1: Input Harmonic FFT with Rectangular Behavior Around 520,000 kHz

As seen in Figure 6-1, the rectangle behavior is occurring around the switching frequency 500kHz. Besides the spread spectrum behavior, the design specifications of the converter were met. Load and line regulation were to be less than 3% and our test showed load is 0.058% and line is 0.141%. Efficiency at full load also meets the design specification, as the required specification was greater than 85 percent and we achieved 94.75 percent. The voltage ripple achieved was 2.5%, which is below the desired 5%.

With the original 12V design working, a few adjustments had to be done to the original design of the board. One of the most significant is the power flow. The original PCB is not well laid out, but the second PCB has linear power flow and more closely follows the recommended design in the IC datasheet. At no load the board output was close to the nominal, but when loaded it did not have any regulation. This could have been a cause from poor soldering or design layout of the PCB. In an attempt to increase regulation, capacitors were connected the output and input the converter. Unfortunately the capacitor at the input was not rated for 24V and melted, which caused a short. After discovering the short, the board no longer operated and no testing was able to be done.

The requirement unable to be met was the 15V/2A step down converter. Through our design and simulation the behavior of the converter was expected but when on the board we were unable to maintain a 15V output when a load as low as 0.1A were applied. During troubleshooting no issues with the board stood out and no errors associated with soldering or design were found. Unfortunately, the IC was shorted when troubleshooting so we could not determine the errors. Due to time constraint, the converter's production was scrapped within our project. Also, technically the inductor current ripple for the functioning 12V converter did not meet design specs because it was smaller than the original range. This is actually a benefit in terms of power loss because the inductor peak-to-peak current is less than what we designed for.

As for the second version of the 12V system was constructed, the goal sought out was to be able to vary the switching frequency and observe the spread spectrum at different switching frequency. The potentiometer we purchased did not have the correct values. The issue seems to have been an ordering error. The potentiometer we ordered has a maximum value of 10 kΩ when a 100 kΩ would have been the correct range for our application. Once assembled, the circuit was shorted and no longer functional. The data was never acquired so there was no way to observe if the design specs were met.

In the first iteration of our board design we had both converters on a single board. However, the second iteration of the design was to have a distinct board for each converter and supply them both using jumper cables from the same source. We recommend in the future that each converter is on a unique board to eliminate concerns that one board's operation is affected by the others. If each converter is on a separate circuit it also makes debugging each converter easier.

The "sync" pin of the chip which controls if the chip was operating in spread spectrum mode was forced to be connected and operated within spread spectrum. Due to the design of the board we were unable to verify the behavior of the converter without spread spectrum activated. In future iterations the benefits of spread spectrum against typical operation behavior could be compared to actual data as opposed to simulated data. This is a simple fix by just adding a jumper to that "sync" pin where it can be toggled between open (regular PWM) and high (SSFM). This is a minor fix that will be beneficial in fully concluding that SSFM is a better option than regular PWM.

Another issue to address is that the original design of the project required a 48V input which was not achieved due to the available chips on the market which operate within that spec. Once a the specification changed from the original 48V value down to 42V input value it would have been wise to use another another chip with a different packaging type. A through hole package would be much easier to solder and troubleshoot in future projects.

6.4 Final Conclusion

The SSFM functionality of the LT8609 is a clever way to reduce EMI for the total system. The measured results were even greater than what we were expecting from simulation and from our perspective there is no real drawback to SSFM other than that it slightly expands the EMI range; however, the dB of this range is much lower than the peak if the chip was operated using regular PWM. There are future steps that can help expand on this research such as viewing the converter in its regular PWM mode and synchronizing multiple converters in SSFM mode to see the effects on the input harmonics. However, from our results we are confident in saying SSFM is a practical way to lessen EMI of DC-DC systems.

7

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Analysis of Senior Project Design

Project Title: Spread Spectrum Buck Converter

Students: Kyle Halloran, Brian Arbiv, Summer Rutherford

Advisor: Taufik

1. Summary of Functional Requirements

This project is a buck converter with an input voltage of 24V and and output voltage of 12V with a full load current of 1A. The converter itself uses spread spectrum technology with a chosen low frequency of 500kHz; it then randomly varies the frequency within a 10% range, or 500-550kHz to lower the EMI.

2. Primary Constraints

One difficulty of this project was how to measure the frequency spectrum since it required such a significant amount of data in a small frequency range to verify spread spectrum functionality. This was solved by using a very large bandwidth oscilloscope. Another difficulty was soldering the board as the LT8609 IC was incredibly small and had a ground plane; this was solved by using solder paste and hot air. In terms of design, we tried to make our converter as standard as possible because it has potential application in the DC house. This limited voltages to standard DC voltages such as 24V and 12V. Ideally the input voltage would have been 48V but we were limited by the IC itself.

3. Economic

Human Capital: This converter is for research involving the DC house. A large motivation for developing DC-DC technology is to benefit homes in rural areas. The installation process and maintenance of this converter will generate jobs.

Financial Capital: This converter utilizes up and coming SSFM technology and could be sold and create profits for investors within a fast paced industry.

Natural Capital: The device uses many electrical components on a PCB. Many of the parts are not recyclable unfortunately. One natural concern is how the PCBs are developed and where they are manufactured, as a more expensive PCB is likely manufactured in a more environmentally friendly way.

Costs: The beginning cost estimate of our project can be seen in Table 8-1. No details were known for the specifics of the converter, so we generally underestimated how many different components were needed. The final bill of materials can be seen in Chapter 10.

Table 8-1: Preliminary Cost Evaluation

Purchase	Cost	Explanation
PCB	$15	Estimated board cost
Inductor	$5	Estimated inductor cost
Capacitors	$3	Input, output, ESR caps
Feedback Resistors	$0.50	Resistor network
LT8609	$0	Sampling the ICs
Banana Plug Connector	$5	For input/output
Total Estimated Cost	$28.5	Underestimate

Timing: This device is not necessarily a marketable product, but rather a test converter to verify viability of spread spectrum technology. With the newest board design, more testing can be done to observe the effects of multiple converters connected to the same bus. A future group might take over the project to look more into spread spectrum technology and see if it is a more practical option than just regular PWM. The converters do not take long to make, with the largest delay coming from the PCB manufacturers and the soldering of components.

4. If Manufactured On a Commercial Basis:

- Estimated number of devices sold per year: ~10,000 devices for DC applications
- Estimated manufacturing cost for each device: $20

- Estimated purchase price for each unit: $30
- Estimated profit per year: $100,000
- Estimated cost for user to operate device: $0.01/hr (electricity cost)

5. Environmental

Environmental impacts that are produced by our project can be attributed to the manufacturing process. The PCBs and electronic components will create a lot of byproduct in their production. E-waste is also a big problem, so to avoid adding to the problem the boards should be recycled or disposed of properly. Another environmental impact is the heavy water use to make the LT8609 chips as IC's typically require a lot of water for each chip (~10 gallons).

6. Sustainability

a. Describe any issues or challenges associated with maintaining the completed device.

Keeping the device cool, dry, and clean will be the biggest challenges in keeping the device operating properly. Right now the converter is not in an enclosed package, so the final product would need to be properly protected.

b. Describe how the product impacts the sustainable use of resources.

The product itself if marketed to a large audience that needs DC-DC converters will be manufactured on a larger scale and will not require resources local to the user.

c. Describe any upgrades that would improve the design of the project.

The main upgrade to improve our project would be to add a jumper that will switch between regular PWM and spread spectrum mode. This upgrade will make it to that the two modes can be easily compared and we can truly see if spread spectrum makes a significant difference to the frequency spectrum. Another upgrade would be to get the 15V converter working so that the synchronous ability could be tested. A final package to protect and easily transport the converter would also improve the project.

d. Describe any issues or challenges associated with upgrading the design.

The jumper would be easy to implement in EAGLE, but there would be another delay in waiting for the PCB. Soldering all the parts is also a challenge, but trying to jump that connection on the current board is very difficult so it would likely require a new PCB. We believe the 15V converter will function fine if the inductance is increased so that is an easy fix. As for the final package, a 3D printed box would potentially suffice but that requires the use of SolidWorks which many EEs are not familiar with; however, many MEs would likely assist.

7. Ethical Implications

It is important to drive the cost of the converter as low as possible. On an ethical standpoint, the cost is important because the targeted customer are those from 3rd world countries which do not have the capital to invest in such products.

Another ethical implication in the safety of the product, the converter needs to be easy to service with proper servicing protocol procedures. The protocol will de-energize the system while being serviced. These steps are necessary to ensure the product routine service are safe.

8. Health and Safety

As with any electrical product there is always the safety concern of failure of the product. However, if the product does fail in operation it would likely just shut off power to anything the 12V is supplying. In general it is a safe converter, but with the open face design and no final package right now there is always the safety concern of accidentally touching or shorting pins while the system is energized. If marketed with a safe final package it is a simple and safe converter.

9. Social and Political

Social and Political issues associated with design, use, or manufacturing of this project is to benefit society as a whole by providing reliable power for communities off the grid such as those in 3rd world countries as the research for this project is linked to the DC House Project.

Social impact includes raising the communities out of poverty by introducing reliable energy which could power learning technologies such as computers.

Through a political lens, this project can increase political ties with foreign countries that will most likely be purchasing or subsidizing this product.

10. Development

The first development we learned from this project was EMI reduction techniques. In researching spread spectrum we learned of just how many techniques have been tested to reduce EMI and we learned a lot about how SSFM really works on a technical basis. The project itself taught us how to use EAGLE and layout a board in a functional way with linear power flow. In terms of tools, we had to use a new, touch-screen oscilloscope with an extremely high bandwidth to capture the necessary data. Overall, we were able to learn the steps all the way from design to build with simulation, the BOM, board design, assembly, and testing.

Timeline of Tasks and Milestones

Winter Quarter Gantt Chart-

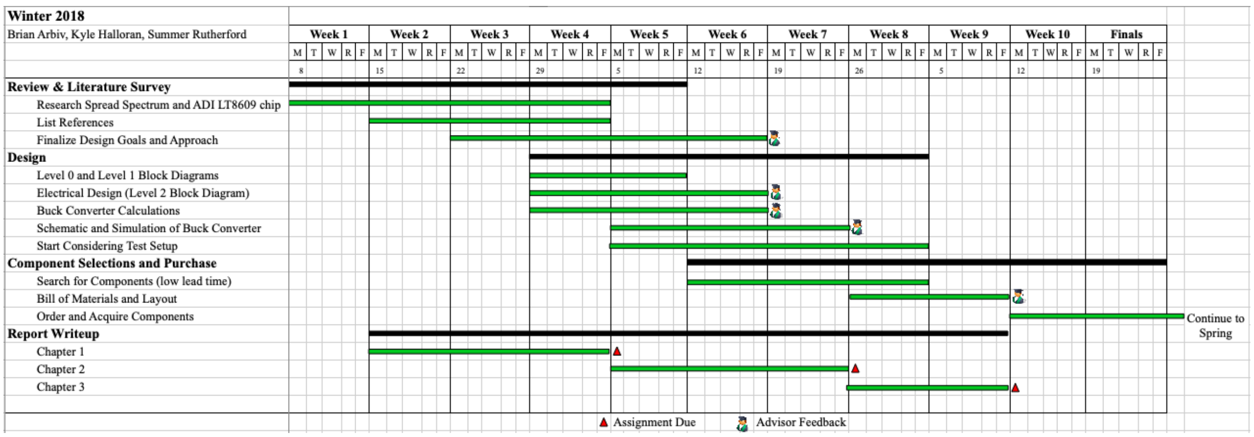

Figure 9-1: Winter Quarter Gantt Chart

Spring Quarter Gantt Chart-

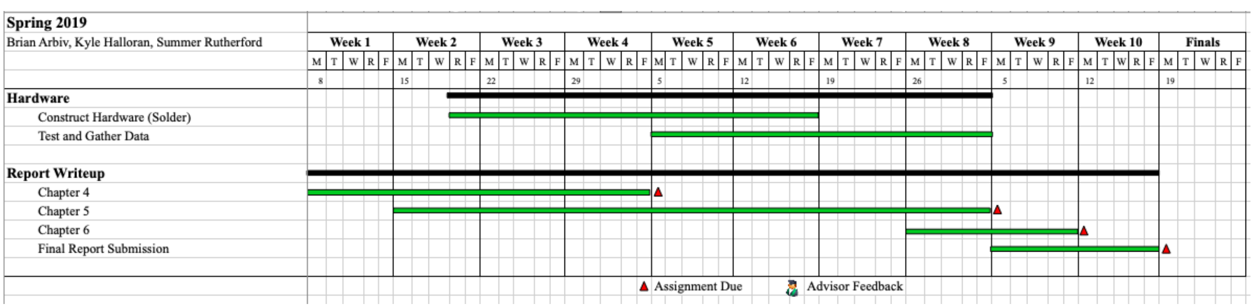

Figure 9-2: Spring Quarter Gantt Chart

10

Bill of Materials

Table 10-1: Complete Bill of Materials

Part on Circuit	Value	Count	Per unit Cost	Total Cost
Input Cap (must be X7R/X5R)	10u	10	0.725	7.25
IntVCC cap	1u	10	0.098	0.98
Tr/SS Cap	0.001u	10	0.024	0.24
RT	86.6k	6	0.29	1.74
BST/SW Cap	0.1u/100n	10	0.033	0.33
Inductor (15V)	22u	3	3.32	9.96
Inductor (12V)	47u	3	5.63	16.89
RFB1 (15V)	182k	6	0.29	1.74
RFB1 (12V)	143k	6	0.47	2.82
RFB2 (12V & 15V)	10k	10	0.067	0.67
FB Cap (12V & 15V)	10p	10	0.039	0.39
Output Cap 1 (electrolytic)	47u	6	0.49	2.94
Output cap 2 (ceramic for ESR)	47n	10	0.097	0.97
Hall Current Sensor	Peak current?	3	5.22	15.66
Female Banana Electrical Jack	4mm	8	1.35	10.8
Header pin kit	N/A	1	7.69	7.69
LT8609A	10 pin, SMD with ground plane	2	0	0
Solder paste	N/A	1	15.95	15.95
Test Points	N/A	2	0.35	0.7
PCB1	N/A	1	18.3	18.3
PCB2	N/A	2	0.5	1
			Total Cost	117.02