CASCADED LINEAR REGULATOR WITH NEGATIVE VOLTAGE TRACKING SWITCHING REGULATOR

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical Engineering

by
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May 2020

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ABSTRACT

DC-DC converters can be separated into two main groups: switching converters and linear regulators. Linear regulators such as Low Dropout Regulators (LDOs) are straightforward to implement and have a very stable output with low voltage ripple. However, the efficiency of an LDO can fluctuate greatly, as the power dissipation is a function of the device's input and output. On the other hand, a switching regulator uses a switch to regulate energy levels. These types of regulators are more versatile when a larger change of voltage is needed, as efficiency is relatively stable across larger steps of voltages. However, switching regulators tend to have a larger output voltage ripple, which can be an issue for sensitive systems. An approach to utilize both in cascaded configuration while providing a negative output voltage will be presented in this paper. The proposed two-stage conversion system consists of a switching pre-regulator that can track the negative output voltage of the second stage (LDO) such that the difference between input and output voltages is always kept small under varying output voltage while maintaining the high overall conversion efficiency. Computer simulation and hardware results demonstrate that the proposed system can track the negative output voltage well. Additionally, the results show that the proposed system can provide and maintain good overall efficiency, load regulation, and output voltage ripple across a wide range of outputs.

Keywords: DC-DC Converter, Switching Converter, Linear Regulator, Low Dropout Regulators (LDOs), Voltage Ripple, Efficiency, Load Regulation, Pre-Regulator

ACKNOWLEDGEMENTS

I am thankful for my advisor, Dr. Taufik, for his guidance and support not only on this thesis, but also in the many classes I have taken with him. Dr. Taufik’s expertise, understanding, and patience greatly contributed to the completion of my degree. My sincere appreciation also extends to my committee members Dr. Tina Smilkstein and Dr. Majid Poshtan.

I would like to thank Frank De Stasi and Arief Hernadi at Texas Instruments for the initial idea proposal and the opportunity to work on this project. Big thanks for the extra guidance during the hardware testing portion.

I am thankful for my parents and my sister for their love, support, and guidance. They have inspired me throughout my life and have taught me to never give up. I would not be where I am today without their sacrifice and unwavering support.

I consider myself fortunate enough to have made good friends throughout this journey. I would like to thank all of them for the help and support they have always extended to me. Brandon Nghe, thank you for being a dependable partner and an even more dependable friend. They are always there when I need them most. Without their encouragement and advice, I may not have made it this far.

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Chapter 1

INTRODUCTION

1.1 The Current State of Power

If one were to take a cursory glance at current electricity distribution methods, it wouldn't be a stretch to assume that the majority of electronic devices run on AC power. Indeed, over 6,000,000 miles of transmission and distribution lines connect houses to generators within the United States alone [1]. However, once in the home, the majority of modern electronics and household appliances actually utilize DC power. In these cases, circuits cannot use the directly delivered power. Instead, it must be converted into a usable and stable form for appliances to use. This is a developing problem as technology becomes smaller, faster, and lighter; power delivery circuits must keep up.

As devices continue to proliferate and get more complex, it is a growing challenge to deliver power to systems. Increasing the sensitivity of devices means that they will be more accurate, but it also means that they will be more sensitive to interference as well. Larger systems, such as those found within self-driving cars will have multiple subsystems – likely requiring different voltage rails, different current draws, and different noise requirements. Thus, power supplies for such devices must be reliable, stable, and compatible. With the growth of electric vehicles, battery packs, solar farms, and other renewable sources of energy, there is a growing demand for efficient and effective power electronics.

1.2 Energy Conversion

Power electronics deals with the control and conversion of electrical energy between different forms and levels. It plays an important role in modern high-efficiency systems by converting voltages and currents into a form suited for user loads. From mobile phones to transmission lines, from powertrains of electric vehicles to satellites up in space, power electronics is ubiquitous in today's technology.

It is important to be able to convert one form of energy into another. There are many methods to achieve this, including AC-AC converters, AC-DC converters, DC-AC converters and DC-DC converters

A DC-DC converter takes a DC voltage and steps it to a different DC voltage level. They are used to step up or down voltages to devices that require a specific voltage to function. Different devices have different operating voltages and it is important to deliver the correct amount to meet specified performance requirements. Providing too much voltage will likely damage components, while too little will prevent them from working properly. It is important to choose the correct topology for the application, whether the goal may be a small form factor, high efficiency, or accurate output regulation. Depending on the application, there are two main forms of converters to choose from: linear regulators and switching regulators.

1.2.1 Linear Voltage Regulators

Linear voltage regulators are a simple yet versatile component that is typically one of the cheapest components in a system. Not only are they fairly simple to implement with a few components, linear regulators have a very stable output with low voltage ripple and a fast transient response. However, the efficiency of a linear regulator can fluctuate greatly, as the power dissipation is a function of the device’s input and output voltages. Thus, in cases where a large step down is needed, power will be dissipated in the form of heat, dramatically decreasing power efficiency.

1.2.2 Switching Mode Regulators

Switching mode regulators are named due to the nature of how it utilizes a switch and a controller to regulate energy levels. These types of regulators are more versatile when a larger step change of voltage is needed. This is because they are able to step voltages at a much higher efficiency than that of linear regulators. Due to their size and flexibility, these regulators have a wide range of applications and can be commonly found in a wide array of modern technologies.

However, designing these regulators tends to be more complex. Not only are these circuits more costly, but also tend to be noisier due to magnetic components and switching components. These issues can negatively affect device performance.

In an ideal world, every system would be compatible with each other; every device would need the same type and amount of power to operate. But we do not live in such a world. We live in a world with inconsistencies and differences: where one device requires a certain voltage, yet another will have an entirely different set of operating specifications. It is increasingly important to continuously improve energy conversion, as modern devices would be helpless without it.

Chapter 2

BACKGROUND

2.1 The Incentive for DC-DC Conversion

The current state of DC conversion will face increasingly difficult challenges in the upcoming decades due to new technologies and the increasing integration of IoT devices in everyday life. This makes DC conversion systems a prime target for potential improvements in upcoming technologies. Those in system design, power engineering, telecommunications, and signal processing are increasingly interested in a power system that is more adaptive to system conditions. Such a system will be appropriate due to its versatility -- saving costs and manpower in future designs.

Those in power electronics strive to achieve better efficiency at a higher power density while maintaining a clean and stable output. As systems become increasingly complex, the range of power specifications continue to increase. Different subsystems within devices have distinct requirements and it is crucial to deliver the correct form and amount of power. For instance, some recent CPUs have stock voltages of only 1.27V [2], newer electric vehicles may need up to 48V [3], while telecommunication systems typically use -48V [4]. With such a wide range, having the ability to deliver appropriate DC power levels is integral to a system’s functionality.

Ongoing changes in electricity demand make power management one of the most important issues on the frontier of upcoming electronics. The demand for stable, cost-effective, and high-performance modules fuel companies to work towards better, more efficient designs. Depending on its application, designers have an assortment of different topologies to choose from.

2.2 Linear Regulator

Linear regulators are step-down circuits that use a closed feedback topology to regulate output voltage [5]. These types of DC regulators are very common in electronics as they are cheap and straight forward to set up.

The primary disadvantage of linear regulators is their inefficiency. Due to the method of how voltage conversion is made, these devices dissipate power, causing them to heat up when there is a large voltage discrepancy between the input and output [6]. Heatsinks may mitigate some of this heat, but will take up valuable area and weight of a device as well as will increase cost.

Linear regulators tend to have a fast transient response, meaning that the output voltage settles very quickly in response to changes in load current or input voltage. In low-power designs, these regulators are also low cost and space efficient. Another significant benefit is that they have a high power supply rejection ratio (PSRR), shown in Equation 2-1.

$$PSRR = -20log\left(\frac{V_{input\ ripple}}{V_{output\ ripple}}\right) \tag{2-1}$$

This means that the output voltage is fairly stable, especially when the input voltage has ripples. In addition, because there are no switching components, linear regulators are an essential component for noise-sensitive applications due to low output noise [7].

In applications that have a small difference between input and output voltages, a linear voltage regulator should be considered. This is especially true with low-power designs, as power loss caused by the efficiency penalty that linear regulators experience will fall within an acceptable amount. Furthermore, the absence of switching components makes these regulators very useful in noise-sensitive situations, especially within frequency synthesizers, low noise amplifiers, control circuits, precision voltage references, high resolution ADC and DACs, and precision sensors. These regulators play an integral role in the delivery of power to communication, medical, and measurement devices.

However, in systems with larger voltage differences or greater load current, the drawbacks of linear regulators become more apparent. The dissipation of larger amounts of power will cause a large amount of heat generation; thus, requiring a heatsink to operate. Due to this shortcoming, linear regulators become a problem in heat-sensitive situations. A switching regulator is the stronger candidate in these circumstances.

2.3 Switching Regulator

A switching regulator will use a switching component to transform voltages into a series of pulses, which is then smoothed out using other components. The input energy is stored periodically, and then released at a different level at the output. This energy is typically stored in a magnetic field of an inductor, while the control loop manages the output level through the switching element. Due to this method of voltage transformation, switching regulators are able to produce output voltage levels that are higher than input levels. However, compared to the linear regulator, a switching regulator will have more components as well as an increased layout complexity.

Switching regulators are more complex than a linear voltage regulator due to both the complexity of the circuit and the interactions between the different signals for these devices [7]. The circuitry requires passive components like resistors and capacitors; semiconductors for the diode and switching element; and magnetics in the form of an inductor. The complexity of the design increases as more components are introduced.

Electromagnetic interference is noise that is either conducted through power supplies or radiated through the air [8]. Switching power supplies generate both [8]. These converters have inherent noise on the output voltage generated by the switching device and inductor. The pulsing of current through the inductor allows the voltages to step to the desired output. Using negative feedback, spikes and ripples in the output can be greatly reduced. However, the bandwidth of the feedback is finite and as a result, ripples cannot be completely eliminated. This characteristic of the feedback loop introduces spurs on the output that has harmonics of the switching frequency, as shown in Figure 2-1 [9].

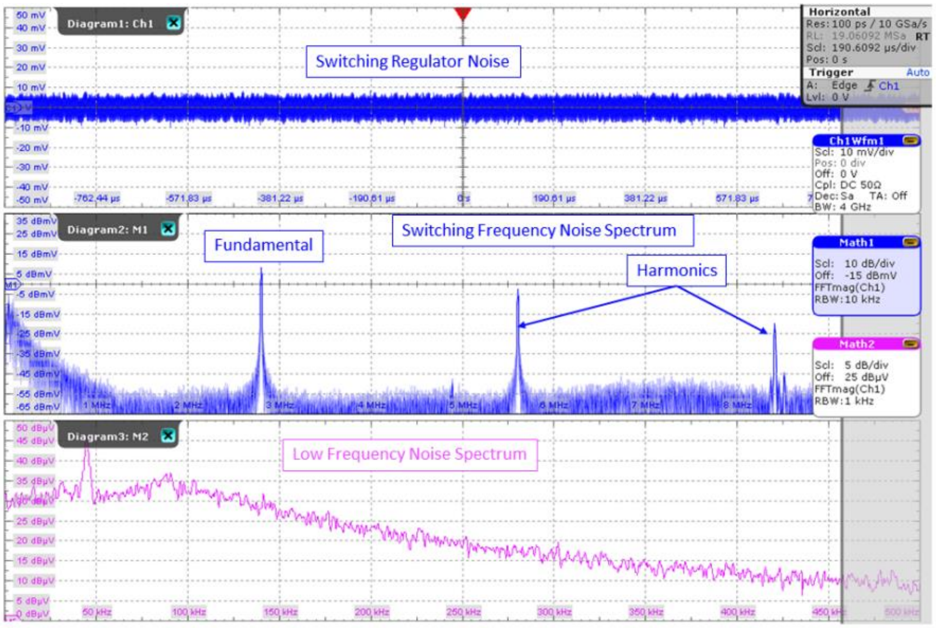


Figure 2-1: Spectrum Plot Showing Harmonics Due to Switching Regulators [9].

These voltage and current ripples can be a major design issue in a noise-sensitive circuit if not carefully filtered. Because the type of noise that switching regulators generate are both conducted and radiated, there is a potential for the regulator to interfere not only with circuits directly connected to it, but also the circuitry around the device. A labor-intensive and time-consuming evaluation process is required to make sure these converters comply with electromagnetic interference regulations in sensitive devices.

One of the most appealing characteristics of switching converters is its flexibility. Different topologies allow for stepping up and down input voltages, or even inverting if needed. They tend to have a wide input and output range. Furthermore, they have low power consumption, take up less space, and are highly reliable. Switching regulators also have a significant advantage compared to linear voltage regulators when it comes to efficiency. This is because the transistor used in switching regulators no longer acts as a variable resistor to dissipate voltages, but is instead utilized as a switch. High efficiency is maintained even across a wide range of input voltages and load conditions.

Switching regulators are used if switching noise is not a big deal, such as digital circuitry, flash memory, and powering LEDs. Switching power supplies are also found in applications where battery life and temperature are important, such as those in the powertrain of electric vehicles, battery management systems for battery cells, phone chargers, and computer power supply units [10]. However, if there are sub circuits in the design that require precise measurements or have sensitive analog sections, the effect of switching noise on the output must be considered. This is apparent in high frequency RF devices, such as frequency mixers, phase locked loops, and laboratory equipment.

2.4 Voltage Converters in Noise-Sensitive Applications

In the realm of DC-DC converters, there is no single best topology for every application; no unified standard exists for the amount of power supply noise that can be considered negligible. Different designs bring advantages as well as disadvantages that system designers must balance. The best option is situational; it would depend on the purpose of the power rail in a particular design. A supply ripple of 100mV may be acceptable when powering digital circuitry, but 100mV could be too large for a sensitive analog circuit.

Switching noise is a phenomenon that is characteristic of designs that involve switching regulators. As the size of devices gets smaller, the frequency of a switching converter must increase because it is inversely proportional to inductor size; when frequency is higher, inductor size can be smaller. Unfortunately, problems arise as frequency increases past 1 MHz. Ripples on the output may couple to other traces on the board and introduce noise and harmonics to the downstream circuitry. This interference has the potential to corrupt critical signals in the circuit, as shown in Figure 2-2 [10].

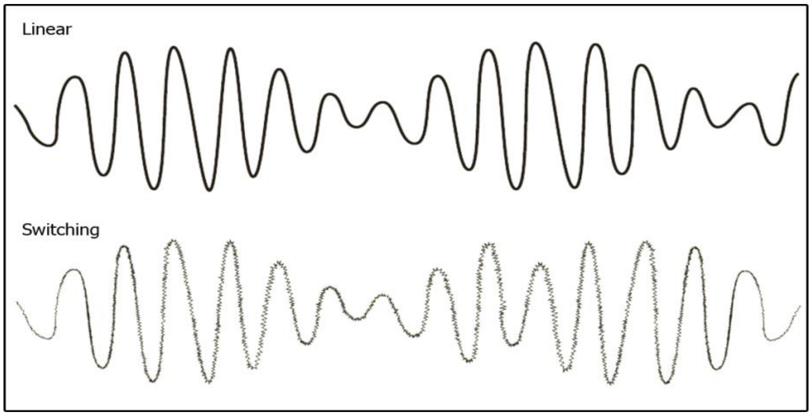


Figure 2-2: Comparison of Circuit Signals Generated from Linear vs. Switching Power Supplies [11].

Low-power circuits are much more susceptible to even very low levels of power rail noise [9]. Examples of hypersensitive circuits include phase locked loops, frequency mixers, low noise amplifiers, and clock oscillators. Noise can cause these circuits to produce an incorrect output, potentially causing a cascade of issues that render a device unusable.

When a non-linear circuit experiences noise, desired frequencies are summed and multiplied such that the output will result in a mixed signal. While mixed signals can be generated using multiple sources, one of the more common -- and often dominant -- sources are due to power supplies [9].

2.5 Addressing Noise Issues

Creating a low-pass RC filter is one of the simplest and cost-effective methods to filter out noise. A resistor is placed in series with the load, while the capacitor connects the load node to ground. An example circuit can be seen in Figure 2-3. Calculating the values of the filter would depend on the frequency of the voltage noise. This method works for both standard linear regulators and switching regulators. However, this simple technique achieves good noise reduction, but does nothing to improve the efficiency of the linear regulator.

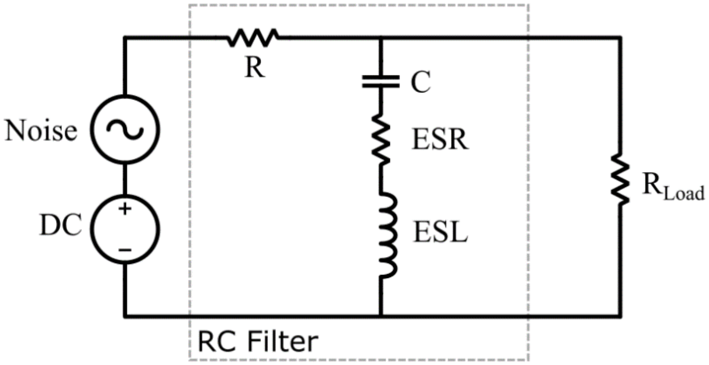


Figure 2-3: Schematic of RC Filter to Attenuate Power Supply Noise

Another passive filtering method that is more commonly done in switching regulators is by placing a filter as the second stage directly after the regulator. This second stage would be an LC filter to attenuate output voltage ripple. An example circuit can be seen in Figure 2-4. This solution has risks due to the resonance frequency of the LC filter: potentially causing instability at certain operating conditions.

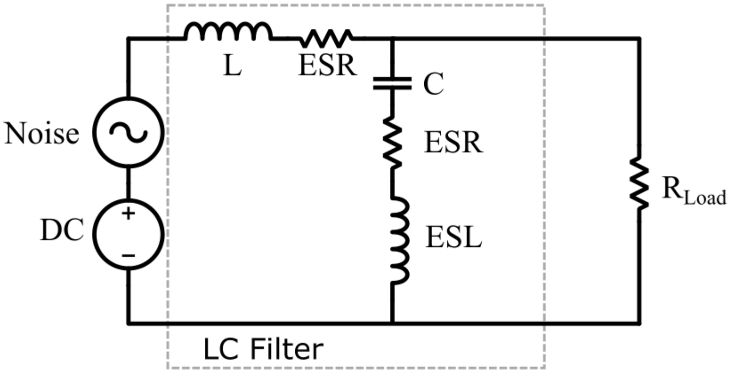


Figure 2-4: Schematic of LC Filter to Attenuate Switching Converter Noise.

Another method of minimizing noise produced by switching regulator is by utilizing the Delta-Sigma modulator controller. This method enables us to use noise-shaping characteristics of the delta-sigma modulator to help attenuate noise and spikes inherent in switching power supplies. Conventionally, a fixed-frequency pulse-width modulation (PWM) signal is used to vary the duty cycle of the control signal for the regulator. However, the PWM has the drawback of producing PWM frequency appearing as noise on the output of the converter. With the ΔΣ modulator, the harmonic tones could be reduced by shaping the quantization noise of the feedback [12]. Once the PWM is replaced by the ΔΣ modulator, the passive components of the switching regulator act as a low-pass filter for the ΔΣ modulator. Furthermore, the amount of switching in the ΔΣ modulator is less when compared to PWM method [13]. This is an important detail, as switching components expend energy to actuate. By switching less occasionally, the ΔΣ modulator based design consumes less energy and thus, is more efficient.

However, the noise shaping technique that the ΔΣ implements reduce noise at desired frequencies at the expense of other frequencies [14]. This means noise will be amplified at frequencies outside of the designed bandwidth. This is disadvantageous in situations where a converter is needed in a system with a wide range of frequencies. The amplification of undesired frequencies may have unintended consequences in high-frequency applications.

Another method to reduce switching noise is to implement the Spread Spectrum Frequency Modulation (SSFM). This technique spreads peak and average noise over a frequency range. The effect on the output is a reduction in peak resonance frequencies [15]. This is most apparent in the fundamental frequency, the third, and the fifth harmonics. In a switching regulator, the frequency of the switching signal will be modulated. The frequency will deviate a certain percentage from the designed frequency. As seen in Figure 2-5, if the frequency of the output is spread across a much wider range, there will be an improvement in EMI, but the output ripple will remain relatively unchanged.

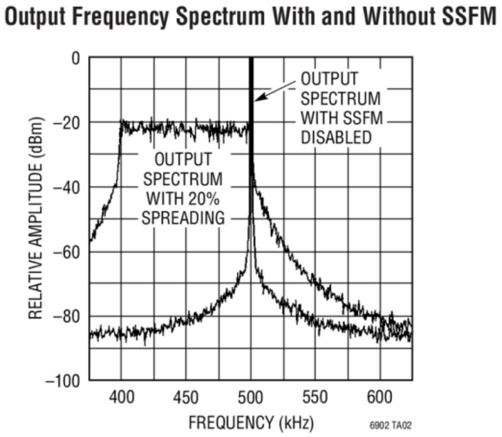


Figure 2-5: Frequency Magnitude of SSFM Signal Compared to Unregulated Signal [16].

Reducing switching noise may also be accomplished via Multiphase regulators. These regulators, as shown in Figure 2-6, are composed of a parallel set of switching converters. Each switching converter will have different switching frequency phases, but a common output voltage node [17]. In this configuration, the inductor current ripple is smaller compared to a single cell due to the phase cancellation effect as depicted in Figure 2-7. A smaller ripple current results in a lower output voltage ripple and switching noise. While this topology is mainly used for higher power applications, the benefits of this technique are still applicable to lower power designs.

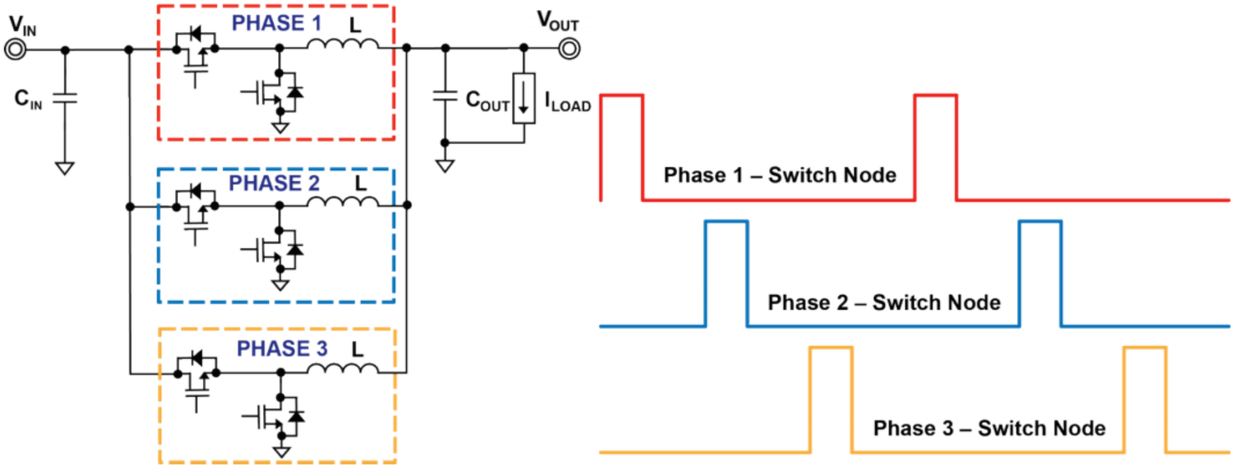


Figure 2-6: Three Switching Regulators Configured as a Multiphase Buck Converter [17].

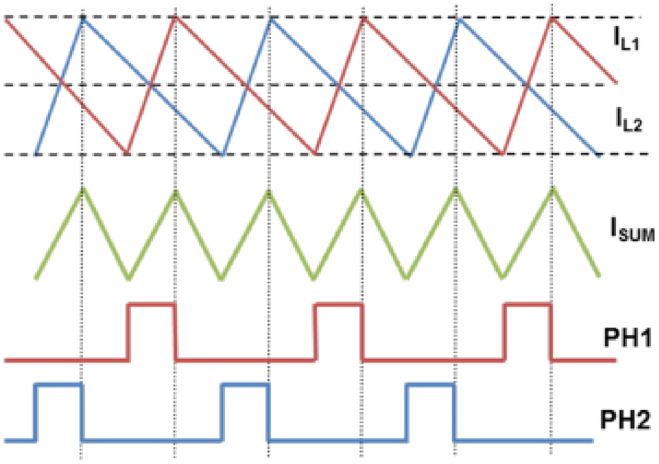


Figure 2-7: Inductor Current Ripple of Multiphase Converter [17].

Another method in reducing noise, particularly on the output or load side of a regulator, is by having a linear regulator as a second stage after a switching regulator to help filter out ripple. The key characteristic that makes linear regulators a good choice is the high power supply rejection (PSR) [9]. The PSR is a measure of output noise compared to input noise. This means that switching noise produced by the switching regulator can be effectively and significantly reduced by using the linear regulator. The circuit configuration of this method is shown in Figure 2-8.

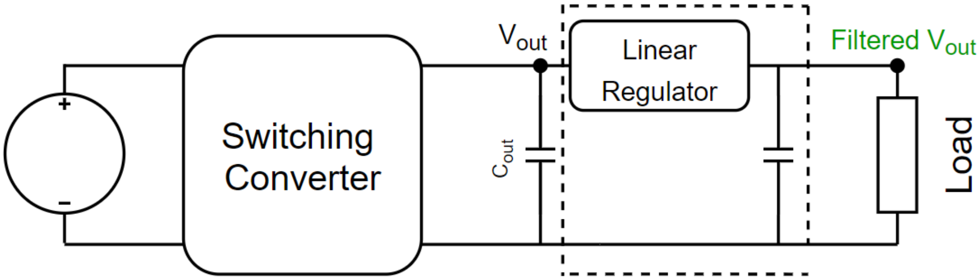


Figure 2-8: Schematic of LDO to Attenuate Switching Converter Noise

In the first stage, the switching regulator converts the input voltage to a voltage slightly above the desired output voltage of the two-stage regulator. Meanwhile, the linear voltage regulator steps down the output voltage of the switching regulator to achieve a very stable output voltage. Because the voltage difference between the linear regulators is minimized, the efficiency of the overall circuit remains high. This method combines the efficiency of a switching converter with the stability of a linear regulator to achieve a DC –DC converter that has good PSR, transient performance, efficiency, and stability. However, the main downside of this circuit is that the difference between the input voltage and output voltage of the linear regulator may vary when the load voltage fluctuates. This results in overall efficiency of the two-stage converter that cannot be maintained and can potentially be low when the difference of the input and output voltages is large.

Using linear regulators to reduce noise is a common solution due to their output stability. However, with great pressure to design energy efficient devices, the poor efficiency of a linear regulator can be a disqualifying condition. Switching regulators have a much better efficiency, but the output contains noise. By combining these two technologies, it is possible to create a power supply that is not only efficient, but also highly stable under various load conditions.

This thesis studies and investigates an improved two-stage pre-regulating buck converter configuration consisting of a buck converter followed by a linear voltage regulator. As output voltage of the two-stage regulator changes, the buck converter stage will dynamically change its output voltage, hence input voltage to the linear stage, to maximize efficiency across the linear regulator. The proposed new design aims to achieve maximum efficiency and high stability across a wide range of output voltages. The design, simulation, and construction of the proposed new two-stage regulator along with results of performance tests will be presented in this thesis.

Chapter 3

DESIGN REQUIREMENTS

As stated in Chapter 2, the basis behind this project is to investigate the design of a DC-DC system composed of a buck converter and linear voltage regulator that will provide an efficient and low-noise DC output. In addition, the output voltage is dynamically changed by feedback loop to maximize efficiency across the linear regulator. As a result, the output should be a stable DC voltage with minimal noise. From a system perspective, the input will be a DC voltage and the output will be a DC voltage that has been stepped down. The overall high-level block diagram can be seen in Figure 3-1.

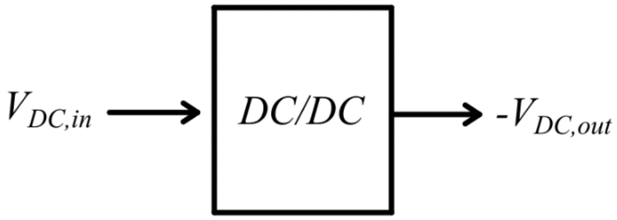


Figure 3-1 Overall System Block Diagram

One of the main applications for this technology is for use in dual-rail operational amplifiers. A negative voltage rail can effectively be created, allowing for a larger amplifier dynamic range. While single supply op-amps only have one supply rail, a dual supply op-amp has two voltage levels with reference to ground: +Vcc and -Vcc. With single-supply designs there can be a pseudo-ground reference, often at half the supply voltage. Signals can swing above and below this voltage instead of 0V.

However, in situations involving audio inputs that swing between positive and negative voltages, a dual supply op-amp is preferred to easily amplify the signal. Likewise, in test and measurement systems, exact DC ground level is important and must be stable. Instead of having a pseudo-ground, it is often easier to generate a negative supply rail [18]. The system discussed in this paper consists of two DC-DC converters: a switching converter and a linear regulator. In the first stage, the switching regulator will invert and adjust the input voltage. In the second stage, the linear regulator will step down the voltage once more, thus establishing a clean and stable negative voltage rail. The feedback loop is configured to maintain a minimum voltage difference across the linear regulator. By constantly keeping the input voltage of the linear regulator close to the output, efficiency is maximized across the second stage across a wide range of outputs. An overview of this operation can be seen in Figure 3-2.

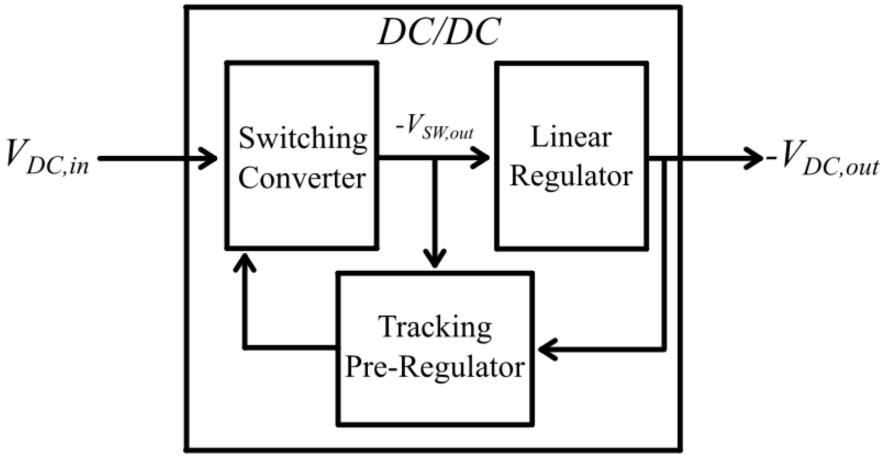


Figure 3-2 Two-Stage System Block Diagram

3.1 Input Requirements

The input will be a nominal DC signal of 15V. A device such as this will likely have an input delivered from a battery or an existing power rail. While 15V is not a typical battery output, a 15V rail is common and cost-effective, especially in analog circuits to deliver enough headroom for amplifiers [19]. A 15V input was chosen not only because it is a common rail, but also in order to be able to demonstrate an improved efficiency without the design challenges associated with higher voltages.

3.2 Output Requirements

Due to the nature of this system, the output voltage has the ability to be varied while maintaining good efficiency. While output voltage can be up to -15V, testing will be done at -1.5V, -3.3V, -5V, -9V, and -12V. These output voltages were selected due to how common they are seen in consumer electronics.

Many microcontrollers, such as the Arduino Uno and Raspberry Pi can output voltages of 3.3V or 5V [20] [21]. Thus having the ability to create the negative voltage will be useful for dual rail-to-rail amplifiers. Likewise, voltages like -9 and -12V are common in audio circuitry. Since the output stage is a linear regulator, we should expect a stable output with less than 2% output ripple.

The output current will be a constant 500mA, regardless of output voltage. In accordance with the testing voltages, this means that the maximum output power will be 6 Watts at an output of -12V and a minimum output power of 0.75 Watts at an output of -1.5V. This current value was chosen with the linear regulator in mind. Often, linear regulators do not carry high current due to heating issues due to efficiency. Thus, as it is, this topology is intended for low-power applications.

An overview of these specifications is summarized in Table 3-1.

Table 3-1: Summary of System Design Requirements

Requirements	**Value**
Nominal Voltage Input	15 V
Nominal Current Output	0.5 A
Minimum Voltage Output	-1.5V
Maximum Voltage Output	-12 V
Maximum Output Power	6 Watts
Output Voltage Ripple	2%
Efficiency	85%

Chapter 4

DESIGN AND SIMULATION

The three blocks of this design consist of an inverting buck converter, a feedback network, and a linear regulator. The first stage will take the nominal voltage input of 15V and convert it into a negative output. Through the feedback network, this voltage is held such that the voltage difference across the linear regulator is minimized in order to achieve good efficiency across the final stage. The final stage takes the input voltage. This design will use the strengths of each type of converter in order to offset weaknesses.

4.1 Inverting Buck Controller Design

4.1.1 Buck Controller Selection

The first stage of the proposed method is a step down (buck) switching converter. There are few regulator topologies that perform positive-to-negative operation; however, a buck topology will be used for the design. In its normal configuration, a buck provides positive output voltage with respect to its input. Therefore, any buck IC must be configured as an inverting buck converter. Figure 4-1 shows the inverting buck topology. It should be noted that since this reconfigured buck topology can step up or step down the magnitude of the input voltage, it is also considered a negative buck-boost converter.

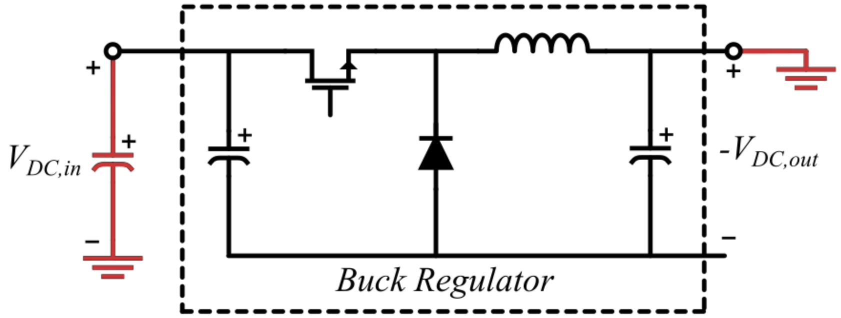


Figure 4-1: Buck Regulator Configured as an Inverting Buck Boost

The sections of the circuit in red are the implemented changes. Special attention needs to be given when selecting a buck regulator for inverting buck boost operation. The regulator experiences larger voltage and current stress since there is a larger voltage difference between the input and output of the device. Equation 4-1 calculates the maximum voltage across the regulator.

$$V_{max} = V_{in} + |V_{out}| \tag{4-1}$$

.

$$V_{max} = 15V + |-15V| = 30\ V$$

As stated in the previous chapter, the input voltage is 15V, while the maximum output voltage will be -12V. Due to the voltage buffer between the linear regulator and output, it is estimated that the output of the switching converter will not exceed -15V. Thus, the regulator must be rated for at least 30V.

A buck controller must be selected in order to handle the stresses that an inverting buck converter topology presents. The LT3976 is an adjustable frequency monolithic buck switching regulator that accepts an input voltage range up to 40V [21]. In addition, the LT3976 is capable of outputting up to 5A, with a switch current limit of 10A. Thus, the LT3976 is capable of handling the voltage and currents required in this design.

4.1.2 Inductor Selection

The inductor acts as an energy storage device so that energy is transferred from input to output. Duty cycle is determined through Equation 4-2. Note that the switching regulator's output voltage will be slightly lower than the linear regulator's output by approximately 2.1V due to the tracking pre-regulator.

$$Duty\ Cycle = \frac{|V_{out}|}{|V_{out}| + V_{in}} \tag{4-2}$$

$$Duty\ Cycle_{Max} = \frac{|-12V - 2.1V|}{|-12V - 2.1V| + 15} * 100 \qquad Duty\ Cycle_{Min} = \frac{|-1.5V - 2.1V|}{|-1.5V - 2.1V| + 15} * 100$$

$$Duty\ Cycle_{Max} = 48.45\% \qquad Duty\ Cycle_{Min} = 19.55\%$$

The maximum duty cycle expected is 48.45%, while the minimum will be 19.55%. Since the output will draw a maximum of 500mA output current regardless of output voltage, Equation 4-3 can be used to approximate the corresponding maximum load output resistance.

$$R_{o,max} = \frac{\left|V_{out,max} - 2.1\right|}{I_{out}} \tag{4-3}$$

$$R_{o,max} = \frac{|-12 - 2.1V|}{500mA} = 28.2\ \Omega$$

The average current through the inductor can then be calculated using Equation 4-4.

$$I_{L,avg} = \frac{(V_{in} * Duty\ Cycle_{Max})}{(1 - Duty\ Cycle_{Max})^2 * R_o} \tag{4-4}$$

$$I_{L,avg} = \frac{(15*0.4845)}{(1-0.4845)^2 * 28.2\ \Omega} = 0.9697\ mA\ \approx 1\text{ A}$$

To proceed, inductor current ripple must be determined. Since current ripple is typically 20% to 40% of average inductor current, Equation 4-5 was used to approximate inductor current ripple.

$$\Delta I = 0.3 * I_{L,avg} \tag{4-5}$$

$$\Delta I = 0.3 * 1 = 0.3\ A$$

Much like other DC converters, the desired current ripple of the inductor plays a large role in selecting the inductance value. Determining critical inductance through Equation 4-6 will give the minimum inductance while maintaining constant current mode.

$$L_c = \frac{V_{in} * D}{\Delta I * f} \tag{4-6}$$

$$L_c = \frac{15 * 0.5}{0.3 * 600kHz} = 41.6\ \mu\text{H}$$

Running at a frequency of 600 kHz, the critical inductance for this system is 41.6 µH. The standard value of 47 µH is chosen.

4.1.3 Input Capacitor Selection

The input capacitor will help to reduce voltage ripple amplitude at the input of the converter. Minimum output resistance is first calculated using Equation 4-7.

$$R_{o,min} = \frac{\left|V_{out,min}\right|}{I_{out}} \tag{4-7}$$

$$R_{o,min} = \frac{|-1.5 - 2.1V|}{500mA} = 7.2\ \Omega$$

An input voltage ripple 5% will be assumed.

$$C_{in} \geq \frac{D_{Max}\left|V_{out,max} - 2.1V\right|}{\Delta V_{in} f_s R_{o,min}} \tag{4-8}$$

$$C_{in} \geq \frac{0.5|-12V - 2.1V|}{(15V * 0.05)(600\ kHz)7.2\ \Omega} \geq 2.175\ \mu F$$

Thus, an input capacitance of at least 2.1μF is needed. Due to datasheet's recommendations, a ceramic 10μF X5R will be used.

4.1.4 Output Capacitor Selection

The output capacitor stores energy and helps to stabilize the control loop of the converter. In addition, the equivalent series resistance (ESR) of the capacitor will help determine output voltage ripple. A low ESR value is desired.

From the datasheet, Equation 4-9 is used to determine a good starting value for output capacitance.

$$C_{out} \geq \frac{300}{\left|V_{out,min} - 2.1V\right| f_s} \tag{4-9}$$

$$C_{out} \geq \frac{300}{|-1.5 - 2.1V| * 600kHz} \geq 138.88\ \mu F$$

Thus, an output capacitance of at least 138.88 μF is needed.

4.1.5 Right Half Plane Zero Considerations

Although an inverting buck boost is built using a normal buck regulator, this topology introduces a right-half-plane (RHP) zero. This zero adds a lagging phase to the loop response, rather than a leading phase. This can lead to potential instability and poor load transient response [23]. Equation 4-10 gives the frequency of where the RHP zero is located.

$$F_{RHP} = \frac{{V_{in}}^2}{V_{in} + |V_{out}|} * \frac{1}{2\pi * L * I_{out}} \tag{4-10}$$

$$F_{RHP,min} = \frac{15^2}{15 + |-15|} * \frac{1}{2\pi * 47uH * 500mA} \qquad F_{RHP,max} = \frac{15^2}{15 + |-3|} * \frac{1}{2\pi * 47uH * 500mA}$$

$$= 50.794\ kHz \qquad = 84.656\ kHz$$

Since the output voltage is varied, the frequency of the RHP zero will range from 50.7kHz to 84.6kHz. Increasing the frequency of the RHP zero will prevent it from interfering with the loop gain of the circuit. From Equation 4-10, it is evident that one of the main factors for the zero frequency is inductance. Having a smaller inductance will increase the frequency of the RHP zero and help to keep it away from the loop gain crossover point. As a result, the inductance value used in the final design should be close to the critical inductance. Additionally, a larger output capacitance will help to maintain stability.

4.2 The Feedback Network

The feedback network is the control element that achieves pre-regulator tracking. This circuit maintains a constant voltage between the terminals of the linear regulator as output voltage is varied. A detailed schematic view of the feedback network is shown in Figure 4-2.

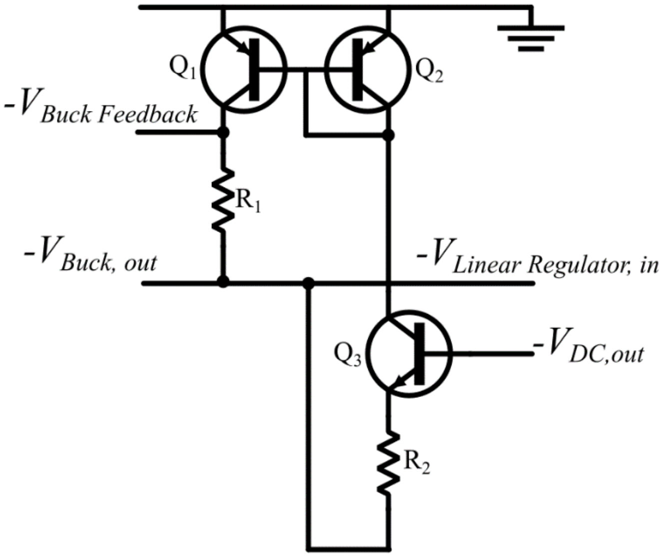


Figure 4-2: Schematic View of Feedback Network

From the datasheet of the buck converter chosen for the design, the feedback node of the converter is typically 1.19V with respect to the ground pin [22]. However, since the ground pin of the switching converter is not the negative output, the feedback node voltage is now with respect to the negative output.

By selecting R_1 = 1.19k, the current across the resistor can be determined using Equation 4-11.

$$I_{R1} = \frac{V_{Buck\ Feedback}}{R_1} \tag{4-11}$$

$$I_{R1} = \frac{1.19\ V}{1.19\ k\Omega} = 1\ mA$$

Thus, the current flowing through $I_{C,Q1}$ is determined to be 1 mA.

$$I_{R1} = I_{C,Q1} \tag{4-12}$$

This reference current will be mirrored by the Q1 and Q2 PNP transistors, such that it will flow through R_2.

$$I_{C,Q1} = I_{C,Q2} \tag{4-13}$$

$$I_{C,Q2} = I_{C,Q3} \approx I_{E,Q3} \tag{4-14}$$

The switching converter must provide enough negative voltage to startup the linear regulator (LDO). This voltage is determined by choosing a proper value for the R_2 resistor. By approximating $V_{BE,Q3}$ to be 0.6V and selecting R_2 = 1.5kΩ, the voltage difference between the switching regulator and the linear regulator can be determined, as seen in equation 4-15.

$$V_{Buck,out} - V_{LDO,out} = V_{BE,Q3} + I_{R1} * R_3 \tag{4-15}$$

$$= V_{Buck,out} - V_{LDO,out} = 0.06 + (1\ mA) * 1.5k\Omega = 2.1\ V$$

Thus, the voltage difference between the input and output of the linear regulator will be approximately 2.1V.

4.3 The Linear Regulator

4.3.1 Linear Regulator Design

The final block in this design is the linear regulator. The configuration of the linear regulator is shown in Figure 4-3.

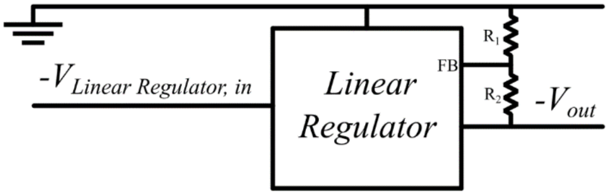


Figure 4-3: System Configuration of the Linear Regulator

R_1 and R_2 control the feedback loop for the correct output voltage. This relationship is shown through Equation 4-16.

$$V_{out} = -1.22\left(1 + \frac{R_2}{R_1}\right) \tag{4-16}$$

Thus, with the datasheet recommendation that R_1=12.1k, Equation 4-17 is used to determine R_2 for the desired output test voltages.

$$R_2 = \left(\frac{V_{out}}{-1.22} - 1\right) R_1 \tag{4-17}$$

$$R_2 = \left(\frac{V_{out}}{-1.22} - 1\right) 12.1k$$

The results are summarized in Table 4-1.

Table 4-1: Summary of Resistance Values for Desired Output Voltages

$-V_{out}$ (V)	R_1 (kΩ)	R_2 (kΩ)
1.5	12.1	2.8
3.3		20.5
5.0		37.4
9.0		76.8
12		107

4.3.2 Linear Regulator Selection

When selecting the linear regulator, it must be able to handle the negative output voltage from the switching regulator. In addition, it must be capable of outputting the appropriate negative voltage. The LT3015 is a negative linear regulator with a wide input voltage range between -1.8V to -30V and an adjustable output voltage range between -1.22 to -29.3V. Additionally, it can output up to 1.5 A [24]. Thus, the LT3015 is a suitable regulator for this design.

4.4 Simulation Results

Once the necessary values have been calculated and obtained from datasheets, it was time to simulate the system. Since the components selected are owned by Analog Devices, LTspice was used as the simulation software. The purpose of simulation is not only to ensure that the system operates as designed, but also to tweak component values and gather data for comparison with hardware data. The schematic in LTspice is shown in Figure 4-4.

4.4.1 Simulation of the Proposed System

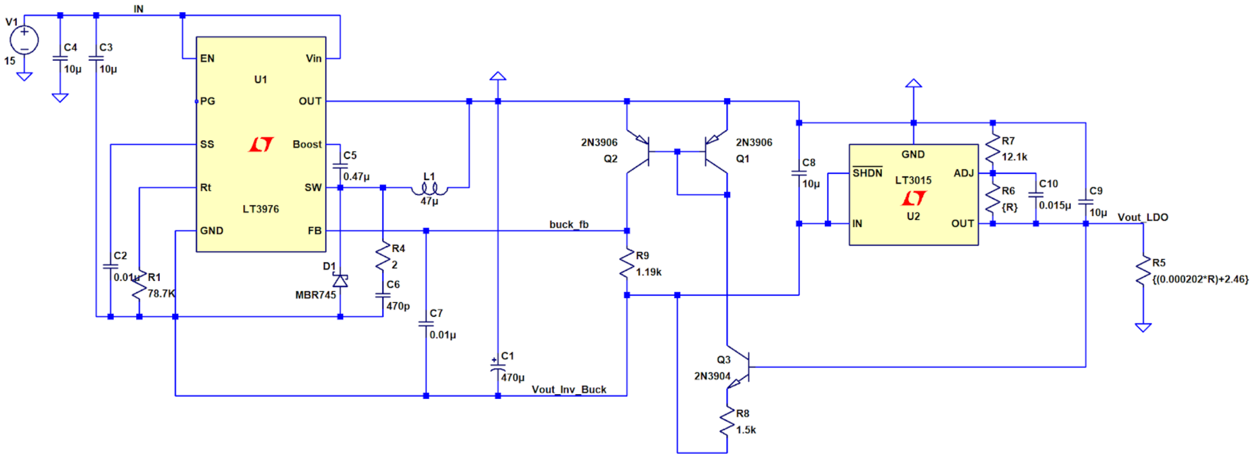


Figure 4-4: Overall System in LTspice

Figures 4-5 and 4-6 portray transient startup responses for output voltages of -1.5V, -3.3V, -5.0V, -9.0V, and 12.0V. Figure 5 is the output of the switching regulator, while Figure 6 is the output of the linear regulator. Notice that the output of the switching regulator is approximately -2.1V below that of the linear regulator across all output voltages, which is consistent with calculated values. In addition, the output of the linear regulator is not only at the desired voltage, but also cleaner than the output of the switching regulator.

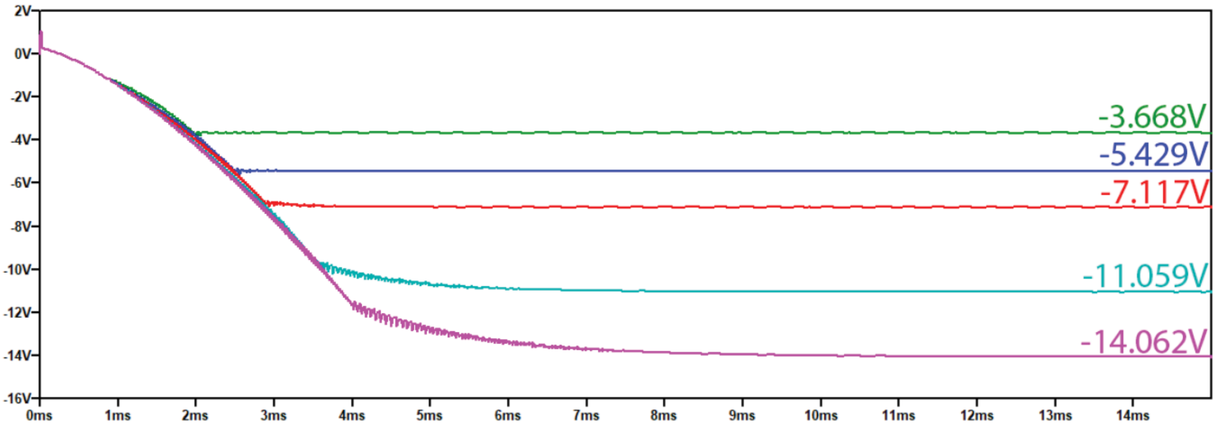


Figure 4-5: Transient Switching Regulator Output Voltage

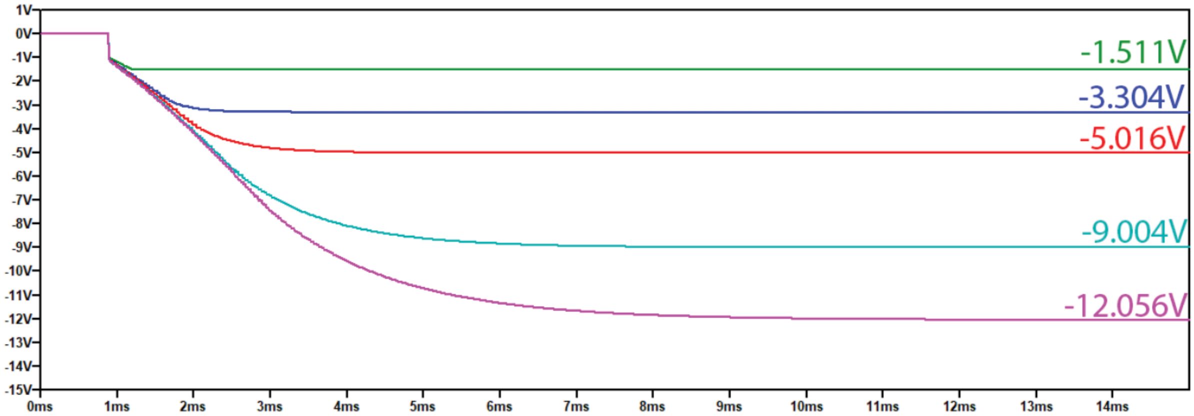


Figure 4-6: Transient Linear Regulator Output Voltage

4.4.2 Comparison to System without Pre-Tracking Regulation

The tracking feedback network is removed to compare the effectiveness of the feedback network. Everything else within the circuit will remain the same except for the feedback circuitry of the switching regulator, which will be set such that the regulator will output -12V. As such, the linear regulator will have a constant input of -12V, while the output voltage varies. The schematic for this test is shown in Figure 4-7.

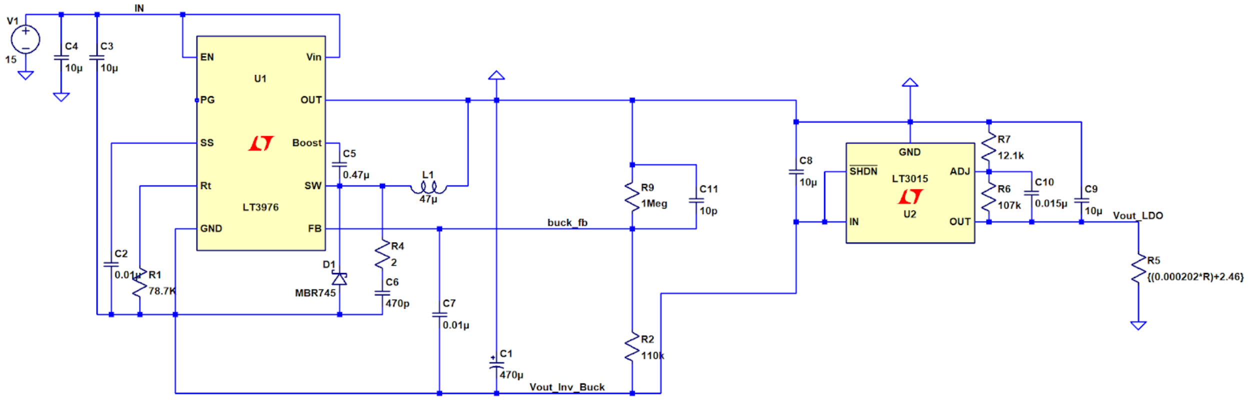


Figure 4-7: System without Feedback Network

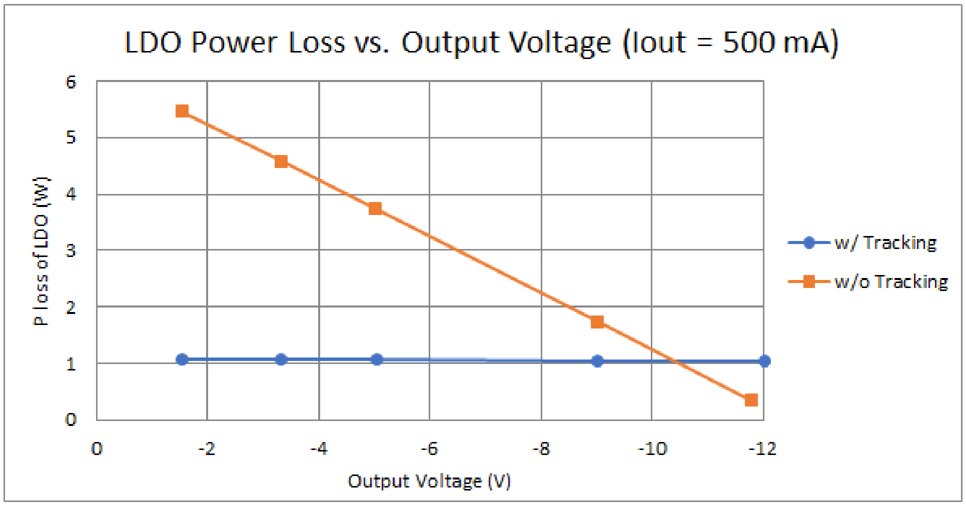


Figure 4-8: LDO Power Loss Across Output Voltages

Shown in Figure 4-8, as the output voltage changes, the power loss across the linear regulator with the tracking network remains fairly constant at about 1 Watt. This is a good indication that the system is operating as designed, as a constant power loss implies that the difference between input and output voltages of the linear regulator stage is also constant. Thus, the output voltage is being properly tracked.

On the other hand, the circuit without the pre-tracking circuit had a much wider range of power loss across the LDO linear regulator. The largest difference can be seen at -1.5V, which is the furthest away from the input voltage. However, at -12V, the system without the tracking circuit performs better. This is because the input voltage is nearly identical to the output voltage, whereas pre-tracking regulating system maintains a constant voltage drop across the linear regulator.

Overall system efficiency is summarized in Figure 4-9. Across all output voltages tested, the tracking pre-regulator circuit consistently outperforms the circuit without one when it comes down to efficiency.

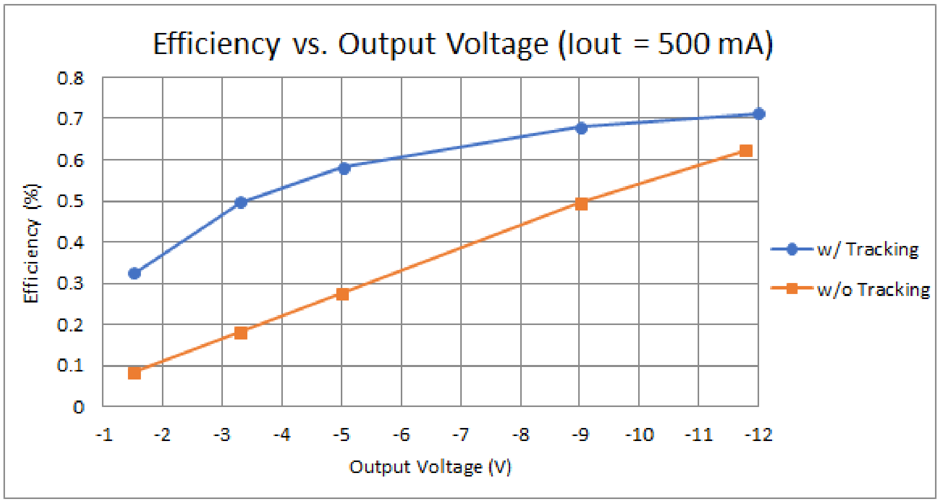


Figure 4-9: System Efficiency Compared with Output Voltage

It should be noted that at constant output current, the efficiency of the tracking regulator circuit will decrease with lower output power, as the power loss across the linear regulator is constant. This means that at lower output power, power lost across the LDO is proportionately larger.

Next, testing is done at various output current levels. Once again, the switching converter of the system without pre-tracking regulation will be configured to output -12V. The output currents to be compared will be 100mA, 200mA, 300mA, 400mA, and 500mA.

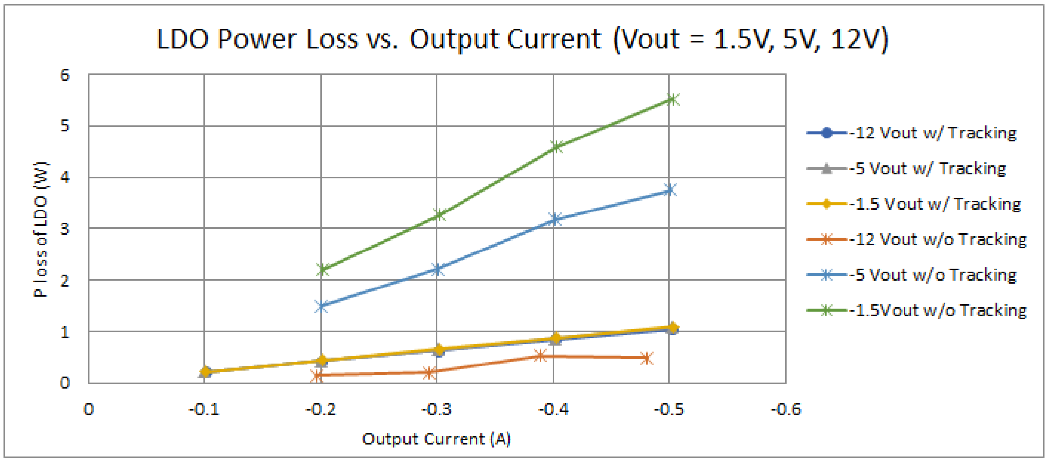


Figure 4-10: LDO Power Loss across Output Currents

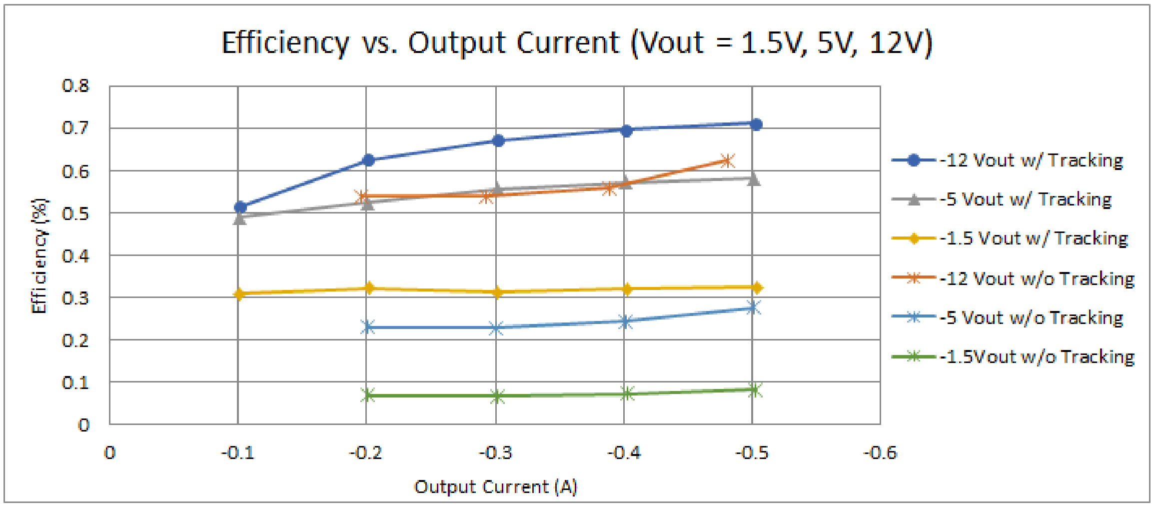


Figure 4-11: System Efficiency Compared with Output Current

Unfortunately, simulation results at 100mA in the system without the feedback network ran into unresolved simulation error and therefore have been excluded from the graph. Once again, the tracking pre-regulator circuit consistently performed more efficiently across all output currents compared to the circuit without. This is reflected in Figure 4-11. Efficiency across output currents remained fairly consistent, with the main difference attributed to power loss across the linear regulator, as shown in Figure 4-10. Linear regulator power loss increases as current increases, which is expected, as current is a function of power. A larger current means more power is dissipated. Since the voltage difference between terminals is the same in the circuit with the feedback network, it is natural that power loss remains fairly consistent across the range of output currents.

4.5 Summary of Simulation Results

Through these simulations, it is evident that there is a notable difference between the circuit with pre-regulation and one without. Total system efficiency has been consistently improved across a range of voltage and current outputs. Not only have simulations proven the effectiveness and viability of the pre-tracking regulator, but they also verified component selection for hardware implementation.

Chapter 5

HARDWARE TEST AND RESULTS

Following the design and simulation, this chapter presents the hardware implementation of the proposed system.

5.1 Board Layout

Care must be taken on board layout for proper operation and minimal electromagnetic interference (EMI) of the switching stage. Having appropriate ground planes, effectively placing components, and minimizing sensitive traces are examples of practices that contribute to a good layout.

The input capacitor is one of the most important component placements for reliable operation of the regulator. It is placed very close to the input of the regulator to minimize inductance and reduce input voltage ripple. Large currents flow through the V_{in} and SW pins of the IC, so traces connecting those pins should be minimized. In addition, components should be placed on the same plane. This is less of a concern, since the board will only be two layers. The exposed pad on the bottom of the LT3076 serves as a heat sink. To keep thermal resistance low, larger traces were used for the node. A large unbroken ground plane is placed on both sides of the board. This ground plane can capacitively link to noisy traces, causing a reduction of noise between different nodes. The FB and RT nodes must be small and kept away from noisier nodes, such as the SW and BOOST nodes. In addition, the ground plane helps to shield them from interference.

The ground of the switching converter and the linear regulator are connected through several small traces. This allows both components to have the same ground while keeping switching noise from coupling to the output. The linear regulator is also placed physically far from the switching regulator for noise reduction. The output has a jumper that adjusts the feedback network of the linear regulator to achieve desired output voltages of -1.5V, -3.3V, -5V, -9V, and -12V. Figures 5-1 and 5-2 show both sides of the printed circuit board that was used for hardware testing. These boards were both manufactured by OSH Park. It is a two-layer board with no components on the back side. A 3-D model for these boards can be seen in Figures 5-3 and 5-4.

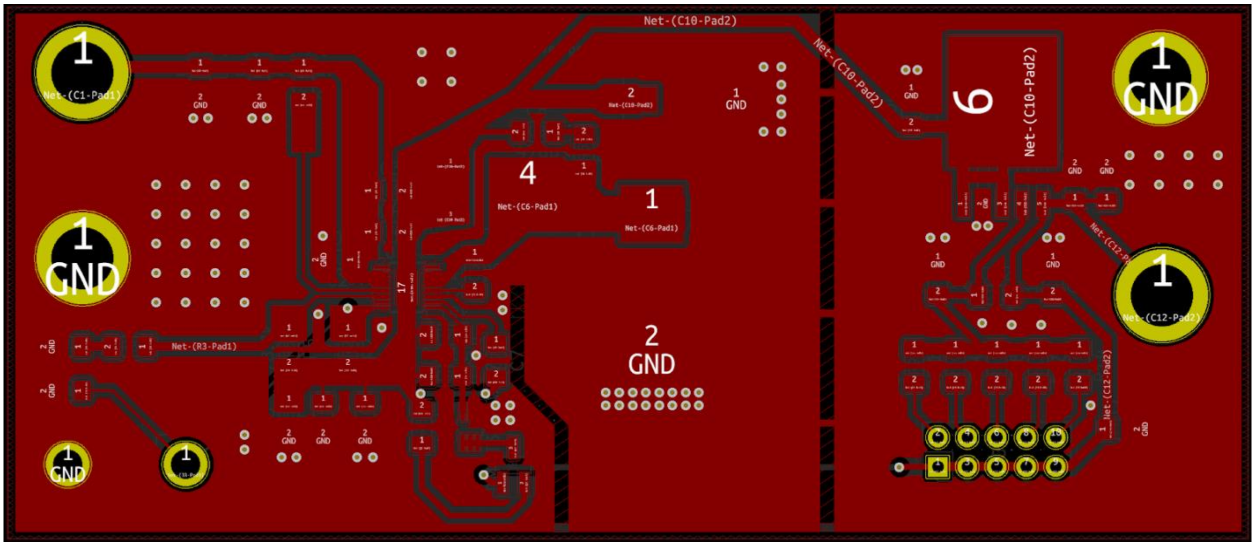


Figure 5-1: Front Side of Circuit Board

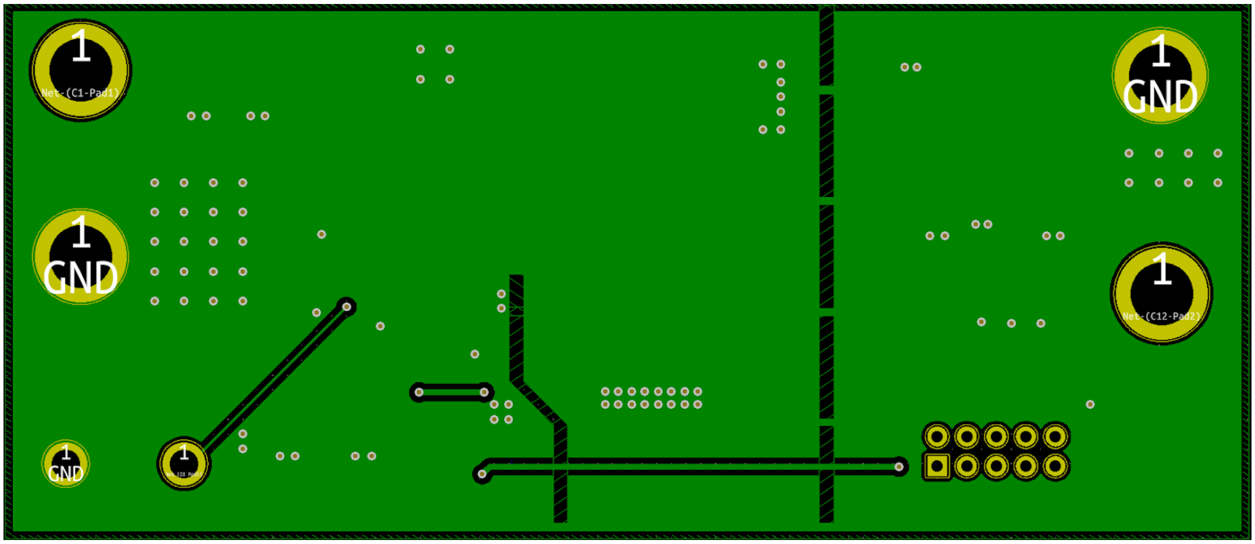


Figure 5-2: Back Side of Circuit Board

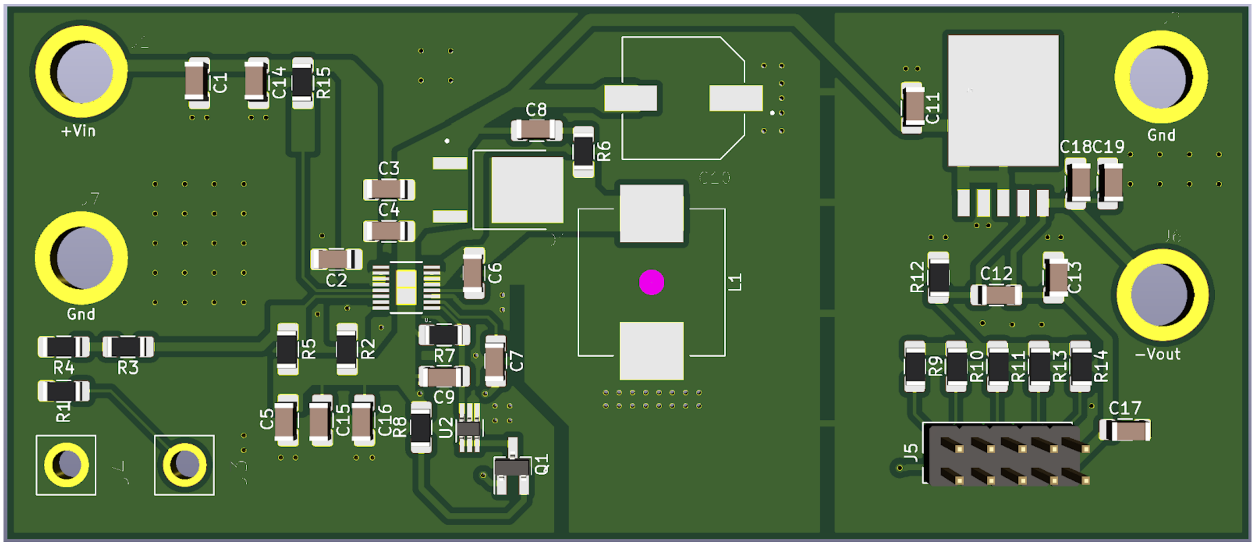


Figure 5-3: 3-D Model of Front of PCB

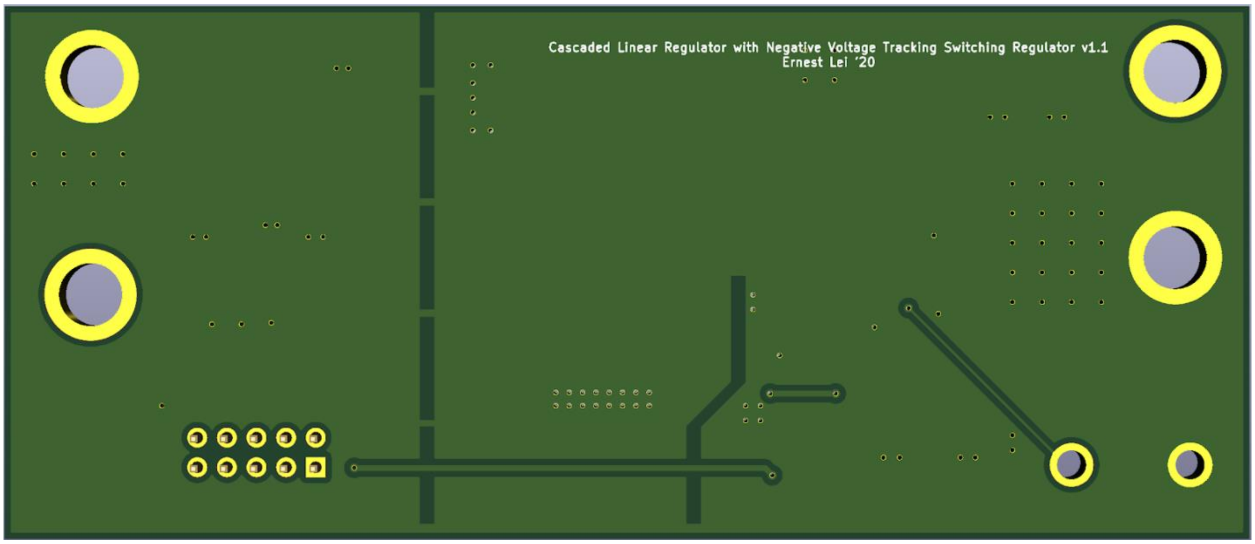


Figure 5-4: 3-D Model of Back of PCB

Once the boards were manufactured, component placement was done by hand. Corresponding components were soldered into place using a reflow oven, soldering iron, and heat gun. The finished board can be seen in Figures 5-5 and 5-6.

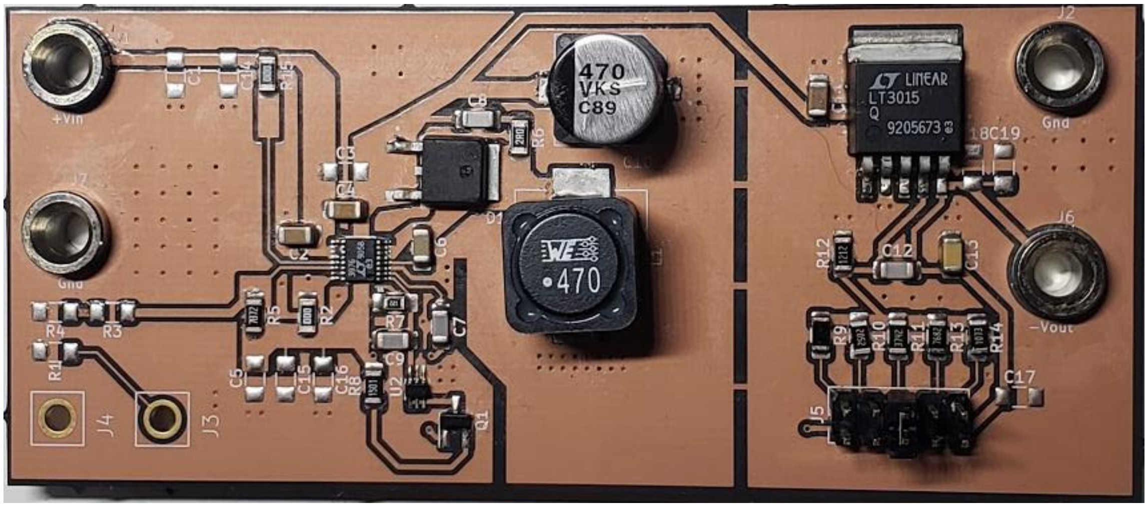


Figure 5-5: Hardware Implementation of Pre-Tracking Circuit Front

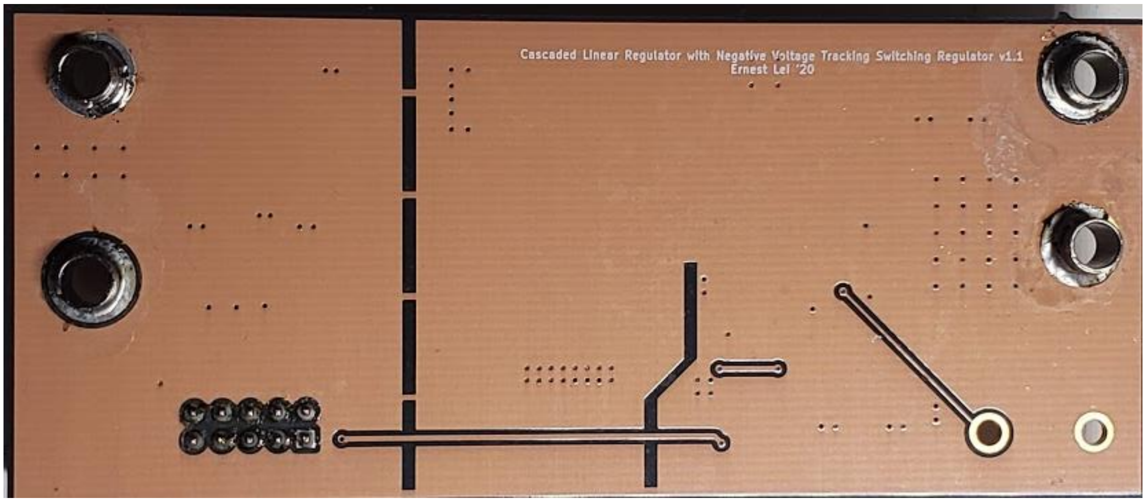


Figure 5-6: Hardware Implementation of Pre-Tracking Circuit Back

5.2 Hardware Testing

Two tests were performed to determine the effectiveness of the pre-tracking regulator circuit. Both tests use the same configuration of testing equipment. A Rigol DP832 Programmable DC Power Supply provides the input power. A power resistor decade box is connected to the linear regulator's output. Agilent Technology's U3401A multimeters were used to measure the input voltage, switching regulator output voltage, and linear regulator's output voltage. Another Agilent multimeter was used to monitor output current. The Extech Ex330 Multimeter was used to monitor voltage out of the switching regulator. Meanwhile, the Tektronix TDS 2002 Oscilloscope was used to view the peak-to-peak ripple of the switching regulator and linear regulator. An overview of this setup can be seen in Figure 5-7.

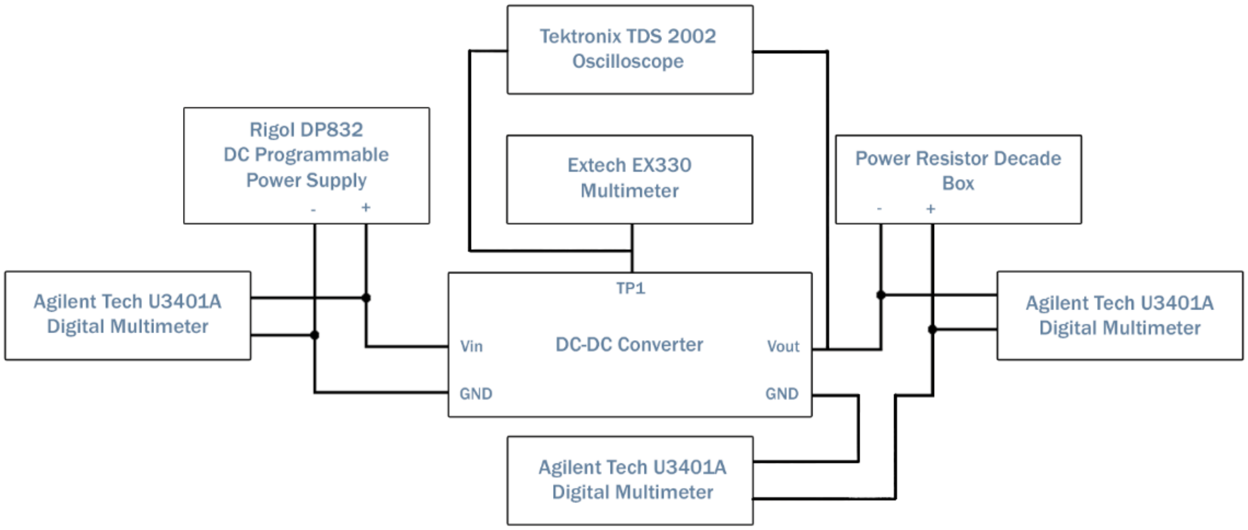


Figure 5-7: Block Diagram of Hardware Test Setup

5.2.1 Testing Pre-Tracking Regulator at Rated Load

In this test, the pre-tracking regulator is tested at full load output current of 500 mA. A constant input voltage of 15V was supplied, while the output voltage was varied. Various data points were recorded, the most important of which are the efficiency and power loss across the linear regulator. This data is summarized in Table 5-1.

Table 5-1: Hardware Full Load DC Characteristics at Varying Output Voltages

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	$V_{OUT, BUCK}$ (V)	$V_{OUT, LDO}$ (V)	I_{OUT} (A)	$V_{diff, LDO}$ (V)	$P_{D, LDO}$ (W)	P_{OUT} (W)	η
14.95	0.13	1.943	3.50	1.49	0.479	2.01	0.965	0.714	0.322
14.95	0.18	2.691	5.11	3.27	0.472	1.84	0.866	1.546	0.492
14.94	0.27	4.033	6.78	4.97	0.505	1.81	0.911	2.515	0.591
14.94	0.42	6.274	10.55	8.94	0.501	1.61	0.804	4.490	0.716
14.93	0.53	7.912	13.45	11.98	0.507	1.47	0.745	6.078	0.768

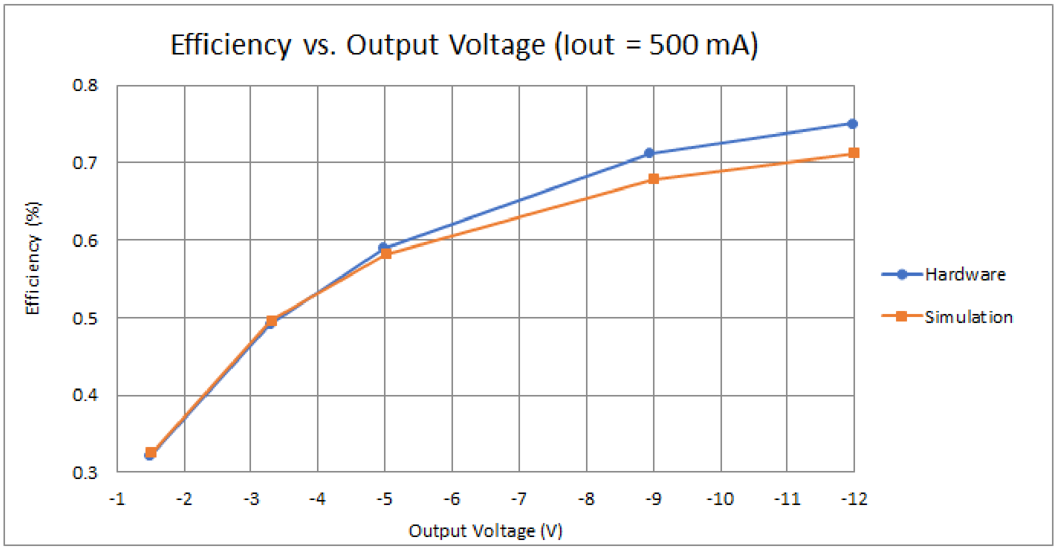


Figure 5-8: Efficiency vs Output Voltage with Tracking

Looking at Figure 5-8, the efficiency of the pre-tracking regulator closely follows the data points gathered from the simulation. Hardware testing shows that the pre-tracking regulator has an efficiency of 32% at -1.5V up to nearly 70% at -12V. This is constant with expected results. In fact, the hardware data consistently overlaps and even outperforms the simulation.

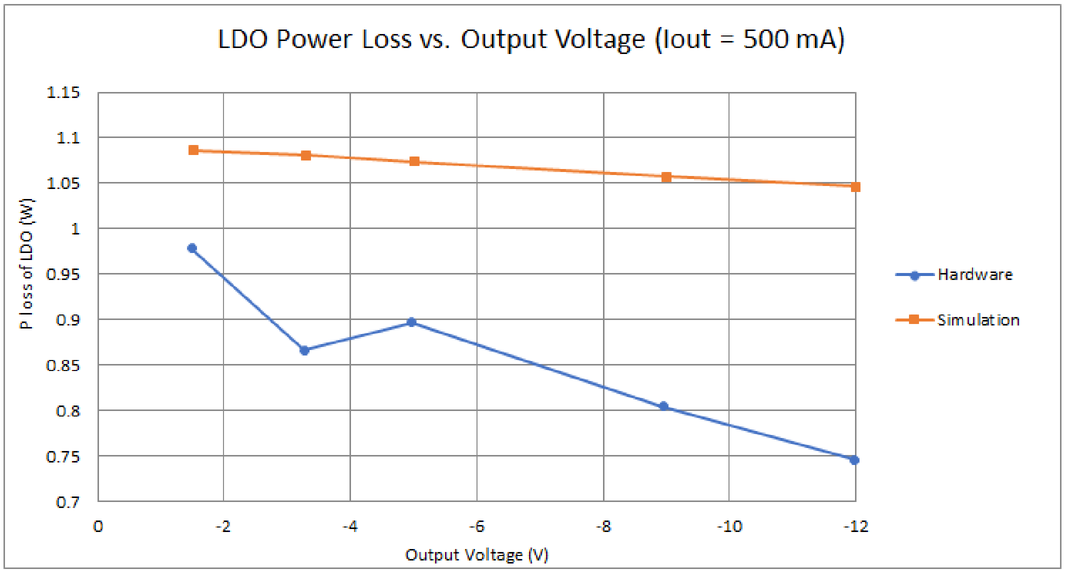


Figure 5-9: LDO Power Loss Across Output Voltages

Figure 5-9 shows an interesting characteristic that emerges from hardware testing. The power dissipation across the linear regulator decreases as the output voltage increases. In addition, power loss from the linear regulator is also consistently lower than the simulation.

5.2.2 Testing Pre-Tracking Regulator at Varying Load

In the next test, efficiency and linear regulator power dissipation were recorded while output current was varied. This was done at output voltages of -1.5V, -5V, and -12V, with an output or load current from 100mA to 500mA in steps of 100mA.

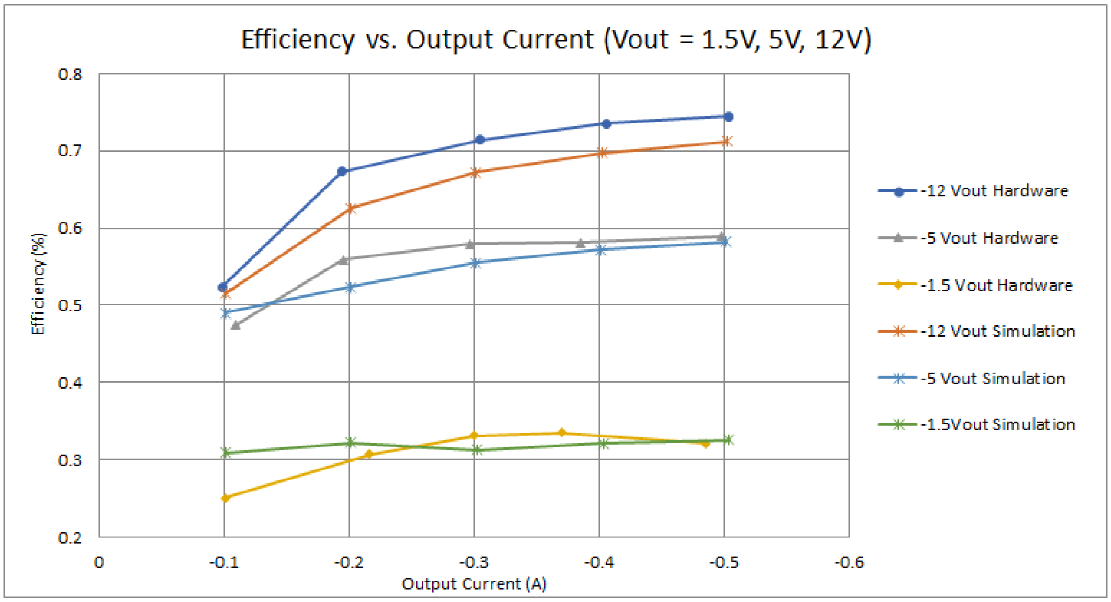


Figure 5-10: Hardware Results of Efficiency with Varying Output Current

For the most part, the hardware results are consistent with the simulations as can be observed in Figure 5-10. At the output voltage of -1.5V, the largest discrepancy was observed. Efficiency was only 25% at a load of 100mA, compared to the expected 30% of simulations. However, as the load increases, the efficiency increases such that it becomes much closer to that of simulations. At output voltage of -5V, efficiency is slightly lower than expected at 100mA, but rises to expected at larger output currents. At -12V, the hardware outperformed simulated results across all load currents.

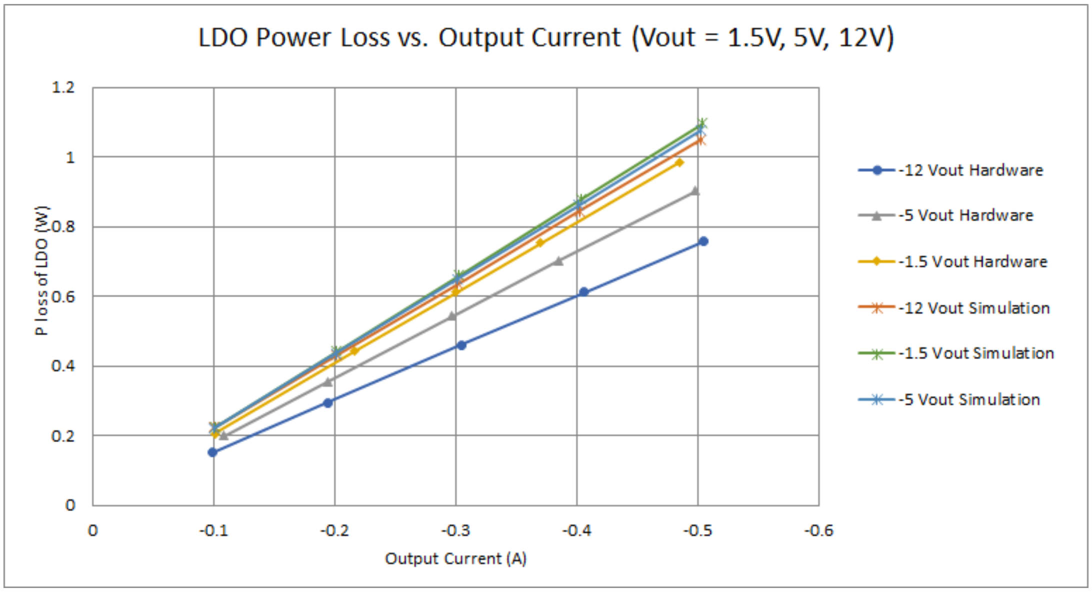


Figure 5-11: Linear Regulator Power loss vs Output Current

Looking at the power loss across the linear regulator shown in Figure 5-11, it is observed that hardware results follow a similar linearly positive trend. As the output current increases, there will be a greater amount of power loss across the linear regulator. Hardware data shows that linear regulator loss is consistently below expected values. It also appears that there is less power loss when the system operates at a higher output voltage.

Notice that linear regulator power loss is constant in simulations, but has a larger variation in the hardware implementation. This implies that this phenomenon can be attributed to the inherent imperfections in a non-ideal real-world circuit.

One potential cause is due to the layout of the feedback loop. In the layout of a switching converter, it is very important to keep the node small. However, due to the addition of the feedback network, the feedback loop is larger than ideal. In addition, the inductor dumps current into the ground plane, which surrounds the feedback node. It is possible that the switching noise is affecting the feedback node voltage, which in turn affects the voltage difference between the switching regulator output and linear regulator output. At higher output voltages, the inductor current has a larger average and peak-to-peak value, which explains why there is a greater discrepancy from simulations as output voltage increases.

5.2.3 Load Regulation

The load regulation of the pre-tracking regulator is measured in order to check the effectiveness of the circuit. In these testing parameters, light load is determined to be at 20mA, while full load is at 500mA. The output voltages will be set to -1.5V, -5V, and -12V. The data is summarized in Table 5-2.

Table 5-2: Hardware Load Regulation Comparison

V_{out}	V_{out} at I_{out} = 20 mA	V_{out} at I_{out} = 500 mA	Load Regulation (%)
-1.5	-1.50	-1.49	0.328
-5	-4.99	-4.98	0.199
-12	-12.00	-11.98	0.125

Comparing the system when it is operating at nearly no load with full load shows that the pre-tracking regulator has good load regulation. The output voltage of this system is stable in situations of both low load current and full load current.

5.2.4 Peak-to-Peak Ripple

One of the primary advantages of the pre-tracking regulator is its ability to output a constant and clean DC voltage despite the more chaotic input from the switching regulator. To ensure this was the case, the peak-to-peak ripple from the output of the switching regulator and the output of the linear regulator were measured and compared. These measurements were made at an output load of 500mA with the output voltage varied. This data is summarized in Table 5-3.

Table 5-3: Hardware Output Voltage Ripple

V_{out}	$V_{pk\text{-}pk\ Switching}$ (mV)	$V_{pk\text{-}pk\ Linear}$ (mV)	Output Voltage Ripple (%)
-1.5	50	21	1.40
-3.3	54	20	0.61
-5	61	20	0.40
-9	67	20	0.22
-12	72	20	0.17

The voltage ripple at the output of the linear regulator is not only consistent, but also small compared to the ripple out of the switching regulator. At all output voltages, the linear regulator effectively cleaned up the noisy signal for an output with much less voltage ripple.

Chapter 6

CONCLUSION

The demand for stable, cost-effective and high-performance DC converter systems incentivizes the search for improvements to existing designs. Step-down converters are the backbone to much of the electrical equipment used daily. As such, they remain an interesting topic and new control schemes are continuously sought after to achieve better performance. A challenge to design DC regulators is to maintain a constant output voltage within acceptable regulation.

This project was successful in developing and demonstrating the effectiveness of a pre-tracking DC converter in terms of a reduced output voltage ripple and an increased efficiency. By cascading a switching regulator with a linear regulator and implementing a new feedback network, it became possible to have the efficiency of a switching converter with the output stability of a linear regulator.

Due to the configuration of the buck converter into an inverting buck-boost, LTspice was a valuable tool in the initial stages of the design to verify components selection and predict overall converter performance. Once appropriate data was gathered, the board was manufactured and tested to be compared with the simulations. Overall, the hardware testing results were consistent with simulation data. Inconsistencies can be attributed to imperfections that exist in the real world. Factors such as layout, soldering quality, parasitic capacitances and inductances, and electromagnetic interference all have a potential effect on the overall system.

The technical requirements that were specified in the design stage were mostly met. Output voltage could be adjusted between -1.5V, -3.3V, -5V, -9V, and -12V with a maximum output load of 500mA. In addition, output voltage ripple fell within an acceptable amount. However, one of the characteristics of the system that deviated from desired specifications is the efficiency. The maximum efficiency observed during hardware testing was 76% at an output voltage of -12V, while the lowest was 32% at -1.5V -- each with a load of 500mA.

There are several aspects of this project that should be taken a closer look at in a future design. When the system first starts up, a large amount of inrush current surges into the circuit.

This current has the potential to not only damage the converter itself, but also subsystems connected to the converter. The problem likely lies with the soft-start configuration of the switching regulator. Placing an electrolytic cap near the source may reduce surge current as well. In addition, the power supply used in testing appears to influence the efficiency of the system. Further testing should be done to narrow down the cause.

Although this design features a limited current output, it would be feasible to achieve a larger output current by adjusting the second stage of the converter. This can be done by placing multiple linear regulators in parallel. In this configuration, output voltage would be maintained, while a wider range of output current can be achieved.

Ultimately, this project has shown that a positive-to-negative pre-tracking DC regulator is a possible avenue for new configurations for DC-DC converters. The proposed method of cascading a switching converter and a linear regulator has the potential to create a system that reacts and optimizes efficiency in response to output voltage shifts. Even at higher output voltages, the power loss across the linear regulator remains fairly constant. Efficiency was maintained, while the output was cleaner. This system, as it is, is only effective at low-power applications, but the ideas explored in this project can potentially be applicable to other future designs as well.

REFERENCES

[1]
The Future of the Electric Grid, An Interdisciplinary MIT Study
https://energy.mit.edu/wp-content/uploads/2011/12/MITEI-The-Future-of-the-Electric-Grid.pdf
2011

[2]
Y.-W. Bai, F.-H. Chang, "Using the load current of the CPU to dynamically control the voltage and reduce the power consumption of PC systems", Proc. IEEE I2MTC, pp. 92-97, May 2012.

[3]
Jian-ming Hu, Yuan-rui Chen, Zi-juan Yang, Study and Simulation of One Bi-directional DC/DC Converter in Hybrid Electric Vehicle, Power Electronics Systems and Applications, pp. 1-4, 2009.

[4]
"'Negative' 48 Volt Power: What, Why and How." Newmar Powering the Network.

[5]
"Switch Mode Power Supply Basics and Switching Regulators." Basic Electronics Tutorials, 2 Mar. 2018, https://www.electronics-tutorials.ws/power/switch-mode-power-supply.html.

[6]
D. Kilani, B. Mohammad, H. Saleh, M. Ismail, "Ldo regulator versus switched inductor dc-dc converter", IEEE International Conference on Electronics Circuits and Systems, Dec 2014.

[7]
R. Perez, "Power conversion techniques for portable EMI sensitive applications", IEEE Int. Symp. on EMC, vol. 1, pp. 487-491, 2000.

[8]
H. K. Patel, "Critical considerations for EMI filter design in switch mode power supply", Proc. IEEE Int. Conf. Industrial Technology, pp. 1843-1848, 2006-Dec.-15-17.

[9]
S. Sandler, "Designing Power for Sensitive Circuits." [Online]. Available: https://www.signalintegrityjournal.com/ext/resources/article-images-2017/2017a/4152SANDLER-Designing-Power-for-Sensitive-Circuits_PAPER.pdf.

[10]
"Linear Regulated vs. Switch Mode Power Supply: EAGLE: Blog," Eagle Blog, 19-Dec-2017. [Online].

[11]
Agilent Technologies, "Understanding the importance of low-noise linear power supplies," Appl. Note

[12]
Sharma, N., Sharma, J., Mishra, S.: 'Design of switching power supply using PWM modulator & Delta-Sigma modulator'. 2016 Conf. on Advances in Signal Processing (CASP), Pune, India, June 2016, pp. 66–71

[13]
Steven K. Dunlap, Terri S. Fiez, "A Noise-Shaped Switching Power Supply Using a Delta-Sigma Modulator", IEEE Transactions on Circuits And Systems-I, vol. 51, no. 6, pp. 1051-1061, June 2004.

[14]
Dunn, Michael, and Luke Weston. “Tearing Into Delta Sigma ADC's.” Hackaday, 7 July 2016, https://hackaday.com/2016/07/07/tearing-into-delta-sigma-adcs-part-1/.

[15]
Kevin Scott ; Greg Zimmer,Spread Spectrum Frequency Modulation Reduces EMI, Analog Devices, Inc., 2019

[16]
B. Schweber, “Using Spread-Spectrum Techniques to Manage Switching Power Supply EMI,” 03-Jun-2014.

[17]
C. Parisi, Texas Instruments (2019). Multiphase Buck Design From Start to Finish (Part 1).

[18]
Mancini, Ron. Texas Instruments, Mar. 2001.

[19]
“SOS Forum • Why audio circuits need higher rail voltage?” [Online]. Available: https://www.soundonsound.com/forum/viewtopic.php?f=22&t=60112. [Accessed: 07-Jan-2020].

[20]
“Arduino Uno Pin Diagram, Specifications, Pin Configuration & Programming.” [Online].

[21]
“Raspberry Pi Compute Module 3 ,” 01-Jan-2019.

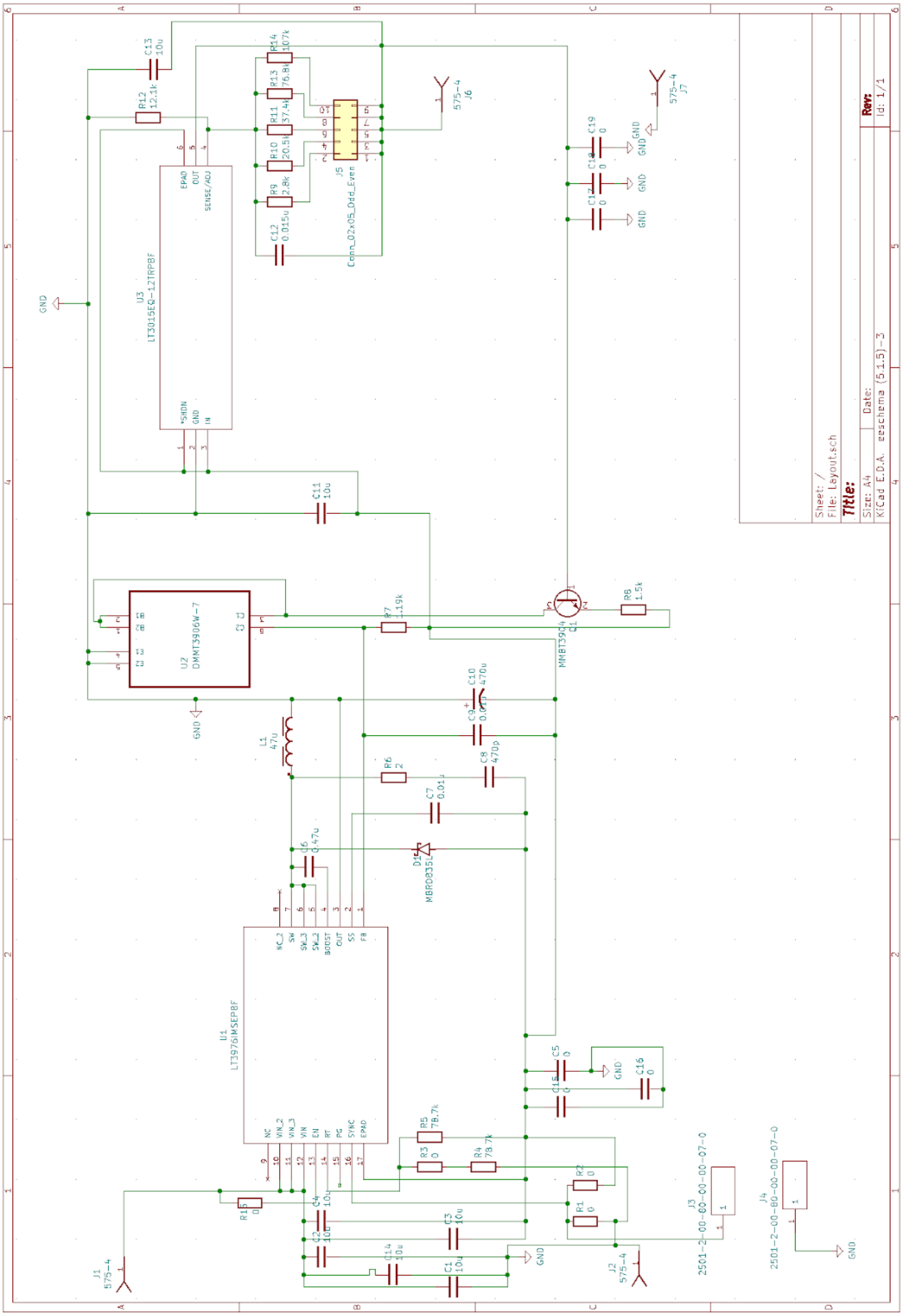
[22]
Linear Technology Corporation, LT3976 Datasheet, 2013

[23]
Frank De Stasi, Texas Instruments, “Working with inverting buck-boost converters”, February 2019,

[24]
Linear Technology Corporation, LT3015 Datasheet, 2011

APPENDIX – A

KiCad Schematic



APPENDIX – B

Bill of Materials

Board REF #	Item	Manufacturer	Description	Part Number	Unit Price	Quantity	Subtotal
U1	LT3976	Analog Devices	Buck Switching Regulator IC Positive Adjustable	LT3976IMSE#PBF	$ 10.00	1	$ 10.00
U2	DMMT3906W-7-F	Diodes Incorporated	Bipolar (BJT) Transistor Array 2 PNP (Dual) Matched Pair 40V 200mA 250MHz 200mW Surface Mount SOT-363	DMMT3906W-7-F	$ 0.36	1	$ 0.36
U3	LT3015	Analog Devices	Linear Voltage Regulator IC 1 Output 1.5A 5-DDPAK	LT3015IMSE	$ 7.27	1	$ 7.27
D1	MBRD1045T4G	ON Semiconductor	Diode Schottky 45V 10A Surface Mount DPAK	MBRD1045T4G	$ 0.89	1	$ 0.89
Q1	SMMBT3904LT1G	ON Semiconductor	Bipolar (BJT) Transistor NPN 40V 200mA 300MHz 300mW Surface Mount SOT-23-3	SMMBT3904LT1G	$ 0.16	1	$ 0.16
R2, R15	0	Panasonic Electronic	0 OHM JUMPER 1/4W 1206	P0.0ETR-ND	$ 0.10	2	$ 0.20
R5	78.7k	Yageo	SMD 78.7K OHM 1% 1/4W 1206	FR-0778K7L	$ 0.10	1	$ 0.10
R6	2	Panasonic Electronic	SMD 2 OHM 1% 1/2W 1206	P17607CT-ND	$ 0.29	1	$ 0.29
R7	1.2k	Yageo	1.2K OHM 1% 1/4W 1206	RC1206FR-071K2L	$ 0.10	1	$ 0.10
R8	1.5k	TE Connectivity	1.5 KOHMS 0.1% 0.4W 1206	RQ73C2B1K5BTD	$ 0.88	1	$ 0.88
R9	2.8k	Vishay Dale	SMD 2.8K OHM 1% 1/4W 1206	541-2.80KFCT-ND	$ 0.10	1	$ 0.10
R10	20.5k	TE Connectivity	20.5 KOHMS 0.1% 1206	A139754DKR-ND	$ 0.92	1	$ 0.92
R11	37.4k	TE Connectivity	37.4 KOHMS 0.1% 1206	RQ73C2B37K4B	$ 0.92	1	$ 0.92
R12	12.1k	Stackpole Electronics	12.1K OHM 1% 1/4W 1206	RSPF2FT12K1	$ 0.03	1	$ 0.03
R13	76.8k	TE Connectivity	37.4 KOHMS 0.1% 1206	A140686CT-ND	$ 0.92	1	$ 0.92
R14	107k	TE Connectivity	107 KOHMS 0.1% 0.4W 1206	A140962CT-ND	$ 0.92	1	$ 0.92
L1	47uF	Würth Elektronik	47µH Shielded Wirewound Inductor 3.8A 60mOhm Max Nonstandard	732-1246-1-ND	$ 2.41	1	$ 2.41
C2, C4, C11, C13	10u	Murata Electronics	10µF ±10% 50V Ceramic Capacitor X5R 1206	490-12456-1-ND	$ 0.69	4	$ 2.76
C6	0.47u	AVX Corporation	0.47µF ±5% 50V Ceramic Capacitor X7R 1206	478-5784-1-ND	$ 0.32	1	$ 0.32
C7, C9	0.01u	Murata Electronics	10000pF ±5% 25V Ceramic Capacitor C0G, NP0 1206	490-6488-6-ND	$ 0.55	1	$ 0.55
C8	470p	KEMET	470pF ±5% 50V Ceramic Capacitor C0G, NP0	399-1213-1-ND	$ 0.28	2	$ 0.56
C10	470u	Panasonic Electronic	470µF 35V Aluminum Electrolytic Capacitors Radial, Can - SMD	493-14715-1-ND	$ 0.98	1	$ 0.98
C12	0.015u	Murata Electronics	0.015µF ±5% 50V Ceramic Capacitor C0G, NP0	490-1758-1-ND	$ 0.56	1	$ 0.56
J1, J2, J6, J7	Banana Connector	575-4	Banana Jack Connector	36-575-4-ND	$ 0.84	4	$ 3.36
J3, J4	Turret	Mill-Max Manufacturing	SINGLE L=5.56MM TIN	ED90581-ND	$ 0.23	2	$ 0.46
J5	Headers, Male Pins	Würth Elektronik	HEADER VERT 10POS	732-2672-ND	$ 1.04	1	$ 1.04
...	Shunts, Jumpers	Würth Elektronik	JUMPER W/TEST PNT	732-2678-ND	$ 0.30	1	$ 0.30
						TOTAL	$ 37.36