CASCADED LINEAR REGULATOR WITH POSITIVE VOLTAGE TRACKING SWITCHING REGULATOR

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ABSTRACT

Cascaded Linear Regulator with Positive Voltage Tracking Switching Regulator

Brandon Khai Nghe

This thesis presents the design, simulation, and hardware implementation of a proposed method for improving efficiency of voltage regulator. Typically, voltage regulator used for noise-sensitive and low-power applications involves the use of a linear regulator due to its high power-supply rejection ratio properties. However, the efficiency of a linear regulator depends heavily on the difference between its input voltage and output voltage. A larger voltage difference across the linear regulator results in higher losses. Therefore, reducing the voltage difference is the key in increasing regulator's efficiency. In this thesis, a pre switching regulator stage with positive voltage tracking cascaded to a linear regulator is proposed to provide an input voltage to a linear regulator that is slightly above the output of the linear regulator. The tracking capability is needed to provide the flexibility in having different positive output voltage levels while maintaining high overall regulator's efficiency. Results from simulation and hardware implementation of the proposed system showed efficiency improvement of up to 23% in cases where an adjustable output voltage is necessary. Load regulation performance of the proposed method was also overall better compared to the case without the output voltage tracking method.

Keywords: DC-DC Converter, Switching Regulator, Linear Regulator, Buck, Efficiency, Tracking, Feedback

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Chapter 1. Introduction

All modern electrical devices require power in order to operate. The power predominantly comes from AC source since it is the most available and accessible, e.g. through common household electrical outlets. However, many of these devices internally utilize DC power and so a method to convert from AC to DC is needed. The amount of DC power required by these devices ranges from low power consumer electronics such as mobile phones and tablets to larger power applications such as electric vehicles (EV). With this wide range of DC power requirement, it is evident that various technologies would be needed to deliver the different DC power levels and to properly operate these devices. An EV, for example, will require much higher level power circuits which would be different from those used for a low power mobile phone.

Furthermore, to improve the efficiency in delivering this power, the voltage level at which the DC power is being delivered will also vary. The larger the power requirement, the higher the operating voltage to minimize the amount of current, which in turn lessens the loss in the process of delivering the power. For example, the high power DC-DC converters for EVs are operating between 36V and 48V architecture [1], while the majority of mobile phones today are currently being charged via the 5 V USB interface.

Regardless of which voltage any of these devices operates, it is important that the circuitry to provide the power can produce a stable voltage at the desired level with very tight tolerance. For example. USB2.0 requires the voltage supplied by high-powered hub ports to be 4.75 V to 5.25 V [2]. To achieve this goal, several voltage conversion techniques have been used and they are commonly called voltage regulators. Depending on the type of source being used by the device, voltage regulators may perform conversion from AC to DC or DC to DC.

For AC to DC converter, there are mainly two methods: linear and switching. The linear method steps down the input AC voltage to a level slightly above the required DC load voltage. The lower AC voltage is then converted to DC with a rectifier circuit. The acquired DC voltage then feeds into a linear regulator to provide the desired output voltage. The switching method directly rectifies the AC input voltage and therefore yields a high DC voltage. This DC voltage is then switched at high frequency and duty cycle to obtain the desired voltage.

When the source is DC, there are mainly two methods to convert to the desired DC voltage: linear regulators and switching converters. The linear regulators are known to have very low efficiency when the input voltage is at a much higher level than the output voltage. They also require power to be dissipated within the circuit which makes them unattractive for high power applications. However, they are simple to design, immune to noise, low cost, and easy to operate; hence, they are a great choice for low power applications. The switching regulators on the other hand are well known for their efficiency; and thus, they are being used in a much broader range of applications from low to high power applications. Switching regulators operate by rapidly turning on and off switches to reach the desired output voltage. This constitutes their major drawback of generating electrical noise both at their input and output stages. Moreover, switching regulators require more complex and larger circuitry than that of linear regulators. However and unlike linear regulators, an important benefit of switching regulators is that they are capable of maintaining very high efficiency operation regardless of the difference between input voltage and output voltage. Switching regulators can also provide an output voltage that is higher than the input voltage (step up function). They are also capable of producing multiple output voltages from a single input voltage.

Depending on the application, both methods of DC-DC conversion can yield a highly efficient and effective conversion process. For highly noise-sensitive, low power applications, such as communication system, using a linear regulator may be the go-to solution. On the other hand, for a system that requires higher power and is more noise-immune, such as lighting or battery charging systems, a switching regulator may be the best choice.

Chapter 2. Background

2.1 Necessity for DC-DC Conversion

Most electric power distribution systems throughout the world utilize alternating current to transmit electrical energy. These AC power systems voltage levels and frequency of transmission vary from country to country but have been standardized to operate using 120/240 volts AC at 50/60Hz.

For direct current systems, there is no such standard. Most appliances cannot directly use the AC power provided; they must convert the AC power to an appropriate DC power to operate. Because DC is not the standard for power transmission, the operating DC voltage for many devices vary. Table 2-1 shows a variety of devices that operate at different DC voltage levels [1][3][4][5].

Table 2-1: DC Voltage Levels of Common Devices and Logic Levels [1][3][4][5]

	-12V	1.25V	1.5V	3V	3.3V	4.5V	5V	6V	9V	12V	36V	48V
Cell-Phone Charging (USB)							✗					
Single Cell Batteries		✗	✗									
Multiple Cell Batteries				✗		✗		✗	✗	✗		
Computers	✗				✗		✗			✗		
Car Battery										✗		
Electric Vehicles											✗	✗

For most devices to operate properly, their input voltage levels must typically be stepped down from the supply. Depending on the application requirements, two ways to accomplish DC-DC conversion are through switching regulators and linear regulators.

2.2 The Switching Regulator

Switching regulators are a method of DC-DC conversion that utilize switching and inductor properties to generate an output voltage as shown in Figure 2-1 [6]. To do this, field-effect transistors (FETs) are rapidly switched on and off, causing the voltage across the inductors to become a pulse waveform, switching between positive and negative voltages. This further generates current toward the output, which in turn is converted to output voltage by the load. By using a controller and a feedback loop, the switching of the FETs is adjusted to achieve the desired output voltage.

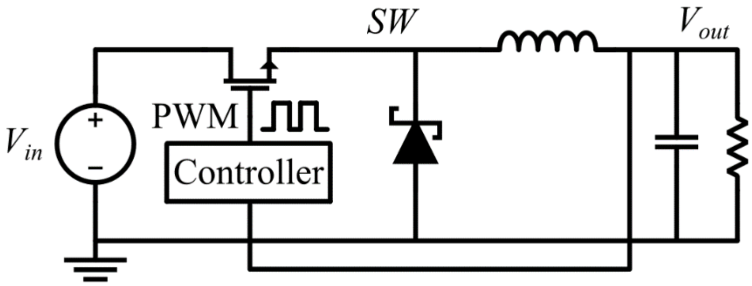

Figure 2-1: Standard Nonsynchronous Buck Converter

Switching regulators are highly efficient, as power is not transferred to the output when the switch is off. Because of this, switching regulators are also capable of handling higher power levels. Switching regulators are also flexible. Depending on the topology used, switching regulators can buck (step-down), boost (step-up) or buck-boost (step-up or step-down) the input voltage. They can also create an output voltage that is the opposite polarity of the input voltage.

The main downfalls of switching regulators design complexity and noise [7]. Switching regulators require many components, including a controller, smoothing capacitors, and an inductor. Operating converters at higher switching frequencies allow for smaller inductors to be used, a faster transient response, and avoid frequency bands where noise would be disruptive [8]. The rapid switching inherent in switching regulators results in a noisy DC output and electromagnetic interference (EMI), which may corrupt other signals in a system.

2.3 Linear Regulator

Linear regulators are an alternative method of DC-DC conversion that converts a higher voltage to a lower voltage by utilizing a series pass device that introduces the necessary voltage drop but dissipates power as heat [9]. A linear regulator circuit typically consists of a linear regulator chip and two resistors to create a feedback. Internally, the linear regulator chip consists of a transistor, error amplifier, and voltage reference as depicted in Figure 2-2. The feedback network with the error amplifier monitor the output voltage. The error amplifier generates a voltage which drives the transistor, which acts like a valve and controls how much current flows from the input to the output to achieve the desired output voltage.

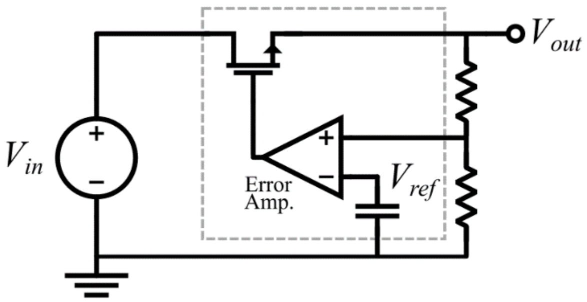

Figure 2-2: Simple Linear Regulator Circuit

Linear regulators are a simple and cheap solution for low power DC-DC conversion. Many of these devices are highly integrated, only requiring a resistive divider to function. They provide a very fast transient response, allowing them to respond very quickly to changes in input or load. Unlike switching regulators, there is no switching noise in linear regulators. This allows them to generate a low-noise output voltage.

The major disadvantages of linear regulators are their lack of flexibility, efficiency, and power capability. Linear regulators are only capable of stepping down the input voltage and are not capable of step-up operation, making them not applicable for some applications. Linear regulators are also only efficient when the input voltage is close to the output voltage. In cases where there is a large voltage difference between the two, the voltage difference translates to power dissipated as heat, resulting in poor efficiency and thermals.

2.4 The Importance of Low-Noise Power in Sensitive Applications

Low-noise power supplies are essential for a variety of low-power applications. This includes RF communication, powering antennas, down-converters, and preamplifiers [10]. With the use switching regulator comes switching noise. Switching noise takes the form of spurs and appears as harmonics of the switching frequency, shown in Figure 2-3 [11].

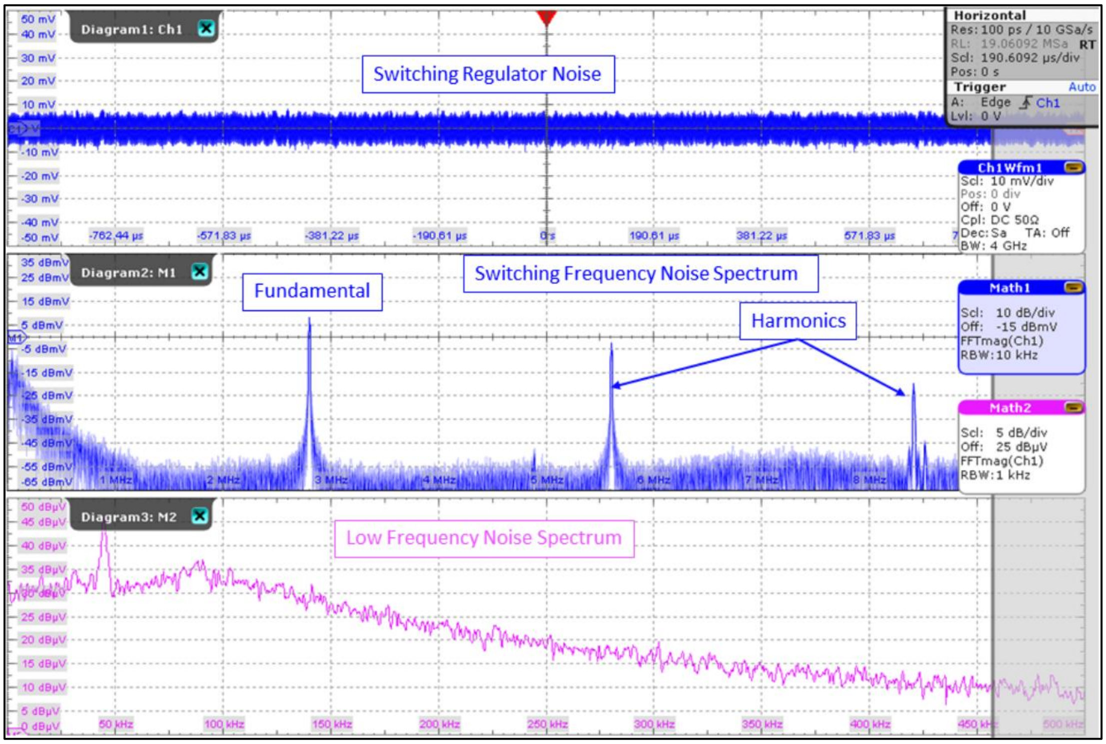

Figure 2-3: Spectrums of Switching Noise w/ Fundamental and Harmonic Spurs [11]

The switching noise may also result in electromagnetic interference (EMI), potentially degrading the performance of nearby systems [12]. Switching noise can superimpose itself onto DC rails and interfere with other signals, as shown in Figure 2-4. Powering noise-sensitive applications with a switching regulator will degrade system performance. Therefore, it is important for powering noise-sensitive systems such as communication and analog applications using low-noise power supply.

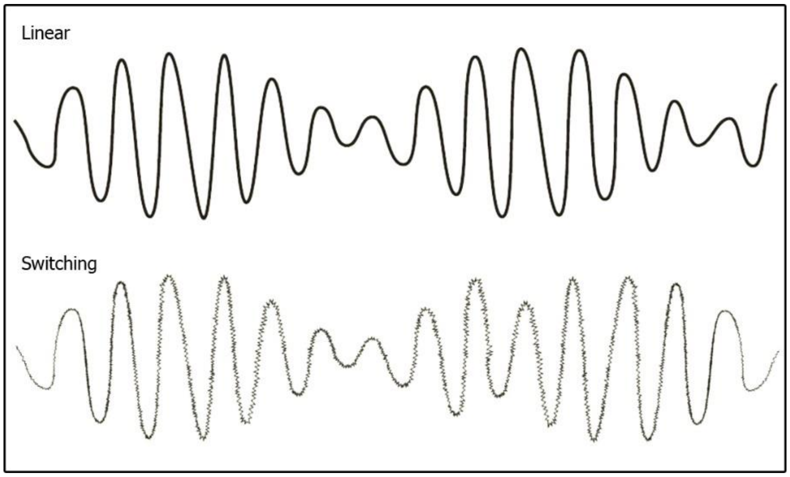

Figure 2-4: Effect of Switching Noise Imposing on Signal [10]

2.5 Noise Reduction in DC-DC Converters

A simple combination of passive resistors, capacitors, and inductors such as that shown in Figure 2-5 can help to attenuate the switching noise in certain frequencies by creating low-pass filters. In some applications, a well-designed low-pass filter may suffice for powering sensitive circuits. The simplest form of this is a low-pass RC filter between the switching converter and the sensitive circuit.

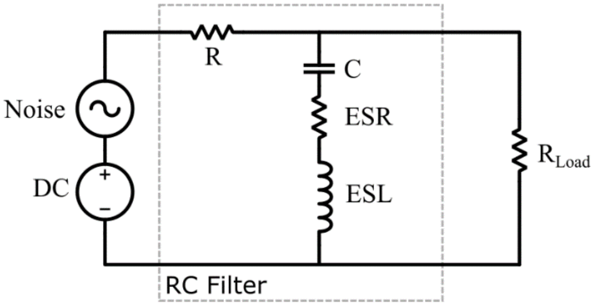

Figure 2-5: Low-pass RC Filter to Attenuate Power Supply Noise

This solution is an easy to implement, entirely passive, and inexpensive method to decrease output voltage ripple [11]. The limiting factor of the solution is the bandwidth of the filter, potentially leaving the harmonic spurs in the output voltage. Additionally, required series resistor will introduce power loss which becomes significant as output power requirement is large. An alternative to the RC filter is an LC filter. An LC filter can be used to achieve better high-frequency attenuation. However, a poorly designed LC filter may result in resonance issue, leading to worse noise in the signal [11]. These low-pass filters also have no effect on EMI.

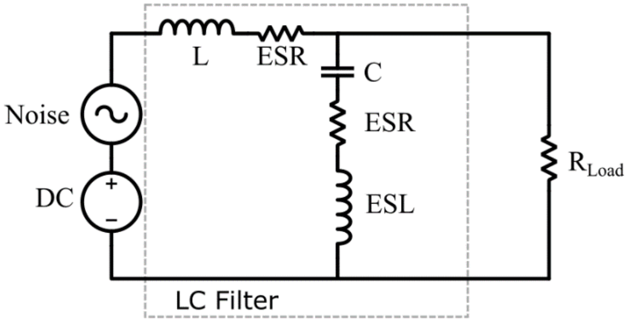

Figure 2-6: Low-pass LC Filter to Attenuate Power Supply Noise

Another noise reduction method is via the Spread Spectrum Frequency Modulation (SSFM). In typical switching regulator, the switching frequency of the device is fixed. This concentrates all the energy of the switching at one frequency and its harmonics. One way to approach this is to spread the switching frequency harmonics into a wider range of the frequency spectrum. All the energy that would be concentrated at one frequency is instead spread out to other frequencies. Frequency spreading results in overall lower peak energy, resulting in lower EMI [13]. This effect can be seen in Figure 2-7. While SSFM greatly improves EMI, it has little effect on output ripple.

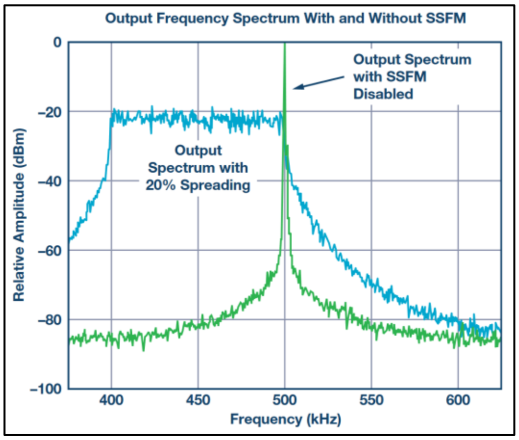

Figure 2-7: Spectrums of a Switching Signal with and without SSFM [13]

Reducing switching noise may also be done by operating switching regulators in parallel while sharing the same input and output. If the switching signals for the paralleled converters are arranged by phase shifting them according the number of switching regulators as illustrated in Figure 2-8, then the configuration is called a multiphase converter.

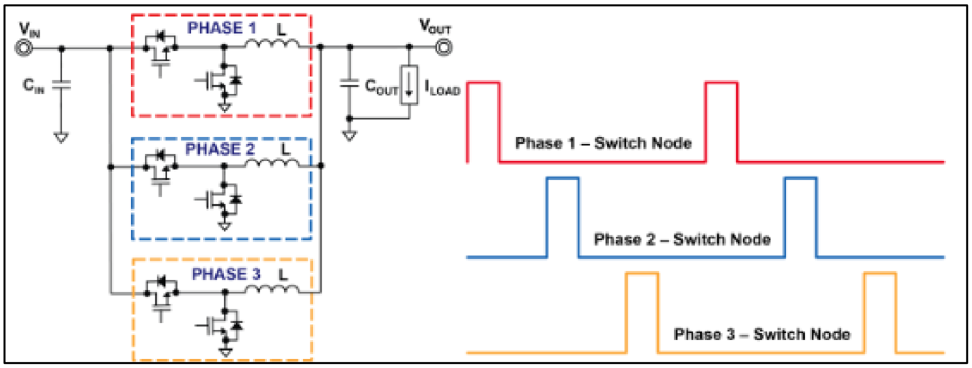

Figure 2-8: Three-Phase Buck Switching Regulator [14]

During its operation, each phase is active for an equal portion of the cycle. By splitting the job of one regulator to multiple parallel regulators, output current ripple will be smaller than each individual inductor current due to the ripple cancellation effect of phase shifting the charging time of each inductor as shown in Figure 2-9 [14]. Consequently, the multiphase configuration offers benefits such as improved efficiency due to decreased in RMS losses, better transient response performance, and higher efficiency compared to using a single converter [14]. In addition, the lower output current ripple also decreases the ripple current of the output capacitors, effectively lowering the output capacitance requirement and its associated cost [14].

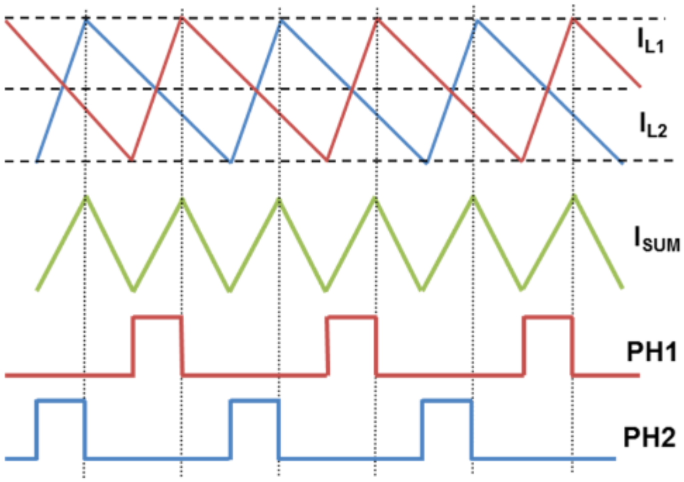

Figure 2-9: Example of Currents in Dual-Phase Switching Regulator [14]

Another method of reducing noise especially on the load side of a regulator by minimizing the output voltage ripple of a switching regulator is by attaching an LDO as the second stage of the converter. An example of converter schematic that shows the two-stage switching-LDO regulator is shown in Figure 2-10.

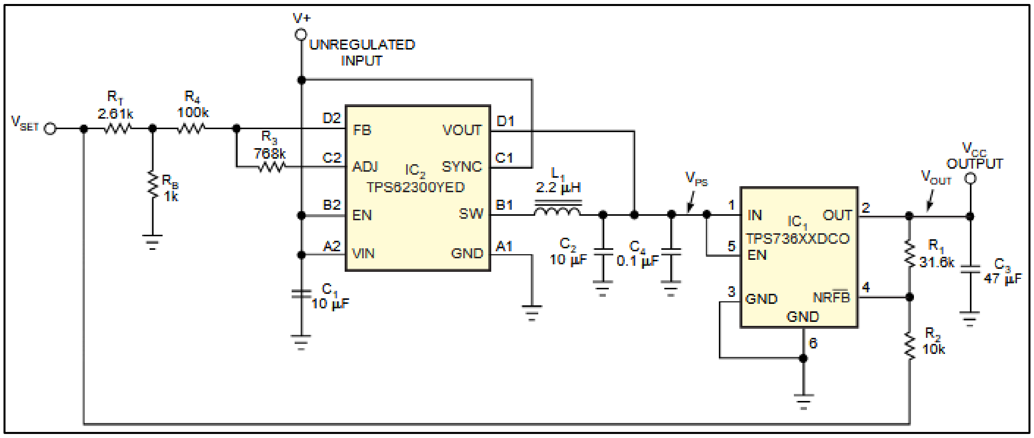

Figure 2-10: Switching Regulator and Linear Regulator Connected in Cascade [15]

As previously mentioned, a major drawback of linear regulators is the power dissipation on the series pass device when there is a large difference between input and output voltages. The larger the difference, the less efficient the regulator is. By having a switching regulator as the first stage, the input voltage to the linear regulator can be dropped much closer to the actual desired output voltage, minimizing the power dissipation in linear regulator as the second stage, and improving overall regulator’s efficiency. Another advantage is that the noisy output voltage from the first stage can now be cleaned up significantly by the LDO’s low-noise performance. Figure 2-11 shows the effect on the Power Supply Rejection Ratio between using a single switching regulator compared to using a single LDO and the cascaded switching regulator-LDO configuration [15]. An LDO’s low output noise and high power-supply rejection ratio (PSRR) allows for clean power delivery. Cascading the switching regulator and linear regulator significantly improves the PSRR of the total system.

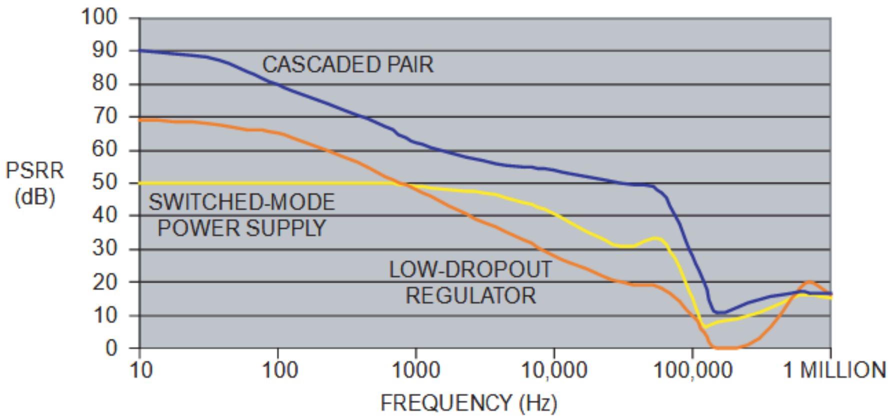

Figure 2-11: PSRR of Cascaded Pair Compared to Switching and Linear [15]

Despite the improved PSRR from the cascaded configuration, one issue remains. That is, if the desired output voltage fluctuates then the voltage differential between input and output of the LDO may not be small anymore; hence, the potential for reduced overall efficiency. This may be addressed by having a mechanism where the output voltage of the switching regulator (input to the LDO) is maintained to always be slightly higher than the output of the LDO. Doing so will keep the overall efficiency very high. This thesis entails the design, simulation, and hardware construction of a proposed new method in the cascaded regulator with the output voltage tracking capability to achieve low power loss in the LDO. The functionality, operation, and performance of the proposed method will be investigated, and results will be compared with those of the existing cascaded configuration.

Chapter 3. Design Requirements

The goal of the project is to test a proposed alternative feedback circuit for a switching regulator and linear regulator cascade. The level 0 diagram of the system shown in Figure 3-1 shows that it will take in an input voltage and generate an output voltage that is dependent on the configuration of the board. This circuit is designed to maximize efficiency.

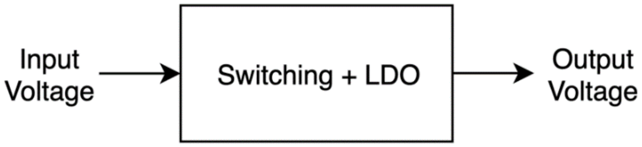

Figure 3-1: Level 0 Block Diagram

The level 1 block diagram shown in Figure 3-2 goes into more detail about the configuration of the circuit.

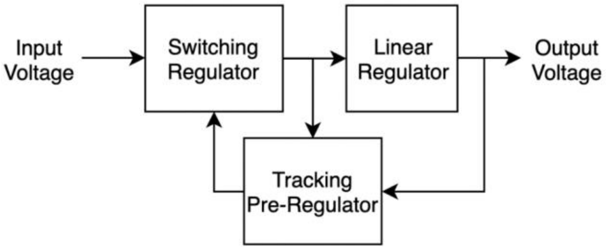

Figure 3-2: Level 1 Block Diagram

The proposed system is broken down into three blocks: the switching regulator, the linear regulator, and the feedback between the two stages. The switching regulator takes the input voltage and the feedback to generate a lower output voltage which is fed into the linear regulator. The linear regulator is used to remove switching noise and generate a clean output voltage. The feedback stage comprising the tracking pre-regulator block is the main focus of the project. It is responsible for creating a feedback voltage for the switching regulator based on the switching regulator's output and the linear regulator's output.

3.1 Technical Design Requirements

The main goal of this project is to design and test a method of improving the switching regulator and linear regulator cascade topology. The focus is to use a circuit that will minimize the voltage difference between the linear regulator's input and output voltage to reduce the power loss. Efficiency and power loss will be measured in the final system. Table 3-1 summarizes the technical requirements for the DC-DC conversion system in this study.

Table 3-1: Technical Requirements of Tracking Regulator for Switching-LDO System

Specification	**Value**	**Justification**
Input Voltage	$15V_{DC}$	This system will use DC input power. This value was chosen as it is a slightly higher voltage than $12V_{DC}$, a common voltage for a power supply.
Efficiency	Greater than 85%	This system will be designed for high efficiency. With the proposed feedback regulation for the linear regulator, the losses are expected to be minimized.
Average Output Voltage	1.5, 3.3, 5, 9, $12V_{DC}$	This system will use a first stage buck switching regulator, so we will only have values less than our input. These values are common low DC voltage levels.
Maximum Average Output Current	500 mA	Due to the use of a linear regulator, output current is limited. The total system is intended for low-power applications.

Chapter 4. Design and Simulation

The main goal of this thesis is to design and test a tracking pre-regulator in a cascaded switching regulator and linear regulator topology. Component selection for each regulator will follow basic converter design. Proper calculation of the values necessary for each component will allow us to construct a hardware prototype that aims to match the theoretical and simulation values and data.

4.1 Standard Buck Converter Design

A switching regulator will consist of a controller, a switching element, an inductor, a diode, input capacitors, and output capacitors. In order to achieve a successful regulator, each component will need to be sized according to a given application.

4.1.1 Buck Controller Selection

Choosing an appropriate buck controller for a given application is essential. In this case, an ideal buck controller will be one that meets the input voltage range, output voltage range, and output currents defined previously in Table 3-1. The LT3971A is an adjustable frequency monolithic buck switching regulator that has a wide input voltage range of 4.3V to 38V, and an adjustable output voltage from 1.19V to 30V. It is also capable of outputting a maximum current of 1.3A. The use of a monolithic regulator eases our design process by not requiring an external MOSFET to be chosen. Figure 4-1 shows a circuit example using the LT3971.

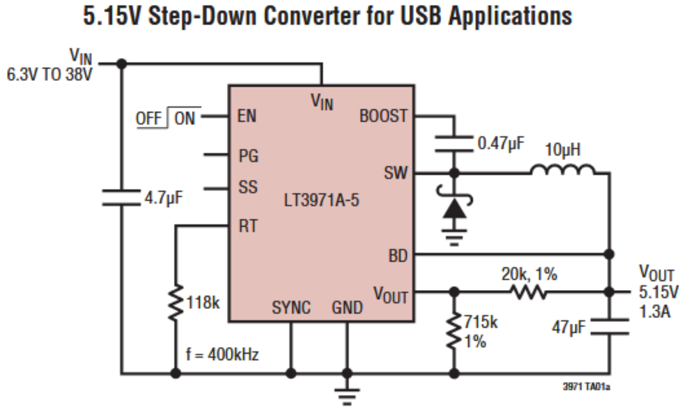

Figure 4-1: Example LT3971A-5 Circuit Schematic [16]

Selection of the regulator’s switching frequency is a tradeoff between component sizing and efficiency. Higher frequencies allow for smaller inductors and capacitors, but they will potentially lower the efficiencies due to increased switching losses. Lower frequencies result in larger inductors and capacitors with better efficiency in general. For this project, switching frequency of 400 kHz is chosen to be between the two extremes.

4.1.2 Inductor Selection

The inductor is the primary source of energy storage in the regulator. It is responsible for storing energy and delivering it to the load and is crucial to the operation of the converter. To size the inductor, it is necessary to find the critical inductance, which can be found using the following equation.

$$L_C = (V_{in} - V_{out})\frac{D}{\Delta i_L f}$$

To achieve good trade-offs in inductance value, a common practice is to use a percent peak-to-peak inductor current ripple Δi_L between 30% and 40% of the maximum load current. In this case, the maximum output current is 500mA. Therefore, the inductor current ripple is approximately 200mA. Furthermore, the switching regulators output voltage will be slightly higher than the linear regulator's output voltage by about 1.9V due to the inclusion of the tracking pre-regulator. The maximum critical inductance is found when the linear regulator's output voltage is 5V. Assuming an efficiency of 90%, the critical inductance is:

$$L_C = \big(15V - (5V + 1.9V)\big)\frac{\frac{5V + 1.9V}{15V * 0.9}}{(200mA)(400kHz)} = 51.75\mu H$$

Ideally, an inductor of 56µH would be chosen. However, due to limitations, the only available value for prototyping was a 47µH. This lower inductance results in higher inductor current ripple and higher RMS losses.

4.1.3 Input Capacitance Selection

The input capacitor of the converter helps smooth out potential disruptions in the power supply voltage. Switching frequency, duty cycle, inductance, and the input voltage ripple determine the required input capacitance.

$$C_{in} \geq \frac{D(1 - D)I_O}{\Delta V_{in} f_s}$$

Again, the maximum capacitance is found when the linear regulator's output voltage is 5V. Furthermore, the capacitance size has to be selected based on a reasonable peak to peak input voltage ripple that will not yield a large capacitance thus increasing cost and converter size as well as not too small of capacitance to give bigger losses due to large input voltage ripple. A commonly used peak to peak voltage ripple is 5% which will be used in this project.

$$C_{in} \geq \frac{\frac{5V+1.9V}{15V*0.9}\left(1-\frac{5V+1.9V}{15V*0.9}\right)(500mA)}{(0.05*15V)(400kHz)} = 41.6\mu F$$

To achieve this input capacitance, a 22uF electrolytic capacitor will be connected in parallel with a 22uF ceramic capacitor. The use of the ceramic capacitor allows for lower equivalent series resistance of the capacitors, reducing losses.

4.1.4 Output Capacitance Selection

The output capacitance of the converter depends on the desired peak to peak output voltage ripple.

$$C_{out} \geq \frac{(1-D_{min})}{8Lf_s{}^2(\frac{\Delta V_o}{V_o})}$$

Because the output will serve as the input to a linear regulator which has high Power Supply Ripple Rejection ratio (PSRR), the output voltage ripple of the switching regulator can be more lenient. As for the input capacitance, the ripple is chosen to be 5% of the output voltage. The minimum duty cycle is experienced when the output of the linear regular is 1.5V.

$$C_{out} \geq \frac{\left(1-\frac{1.5V+1.9V}{15V*0.9}\right)}{8(47uH)(400kHz)^2(0.05)} = 26.2\mu F$$

4.2 Linear Regulator Selection

When selecting the linear regulator, it is necessary to find one capable of handling the output voltage from the buck regulator, with adjustable output voltage and output current as described in Table 3-1. The LT1963A is a regulator that allows input voltage up to 20V, has an adjustable output voltage from 1.21V to 20V, and delivers a maximum output current of 1.5A; thus, fulfilling the needs of the design for this project.

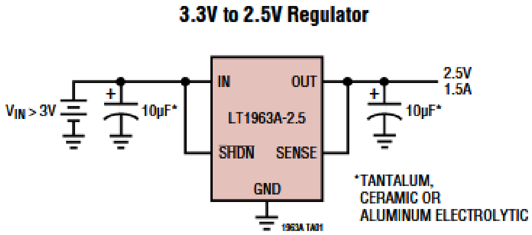

Figure 4-2: Example LT1963A-2.5 Circuit Schematic [17]

The output voltage is set by the ratio of two resistors in a resistive divider to the ADJ pin, which references 1.21V to ground.

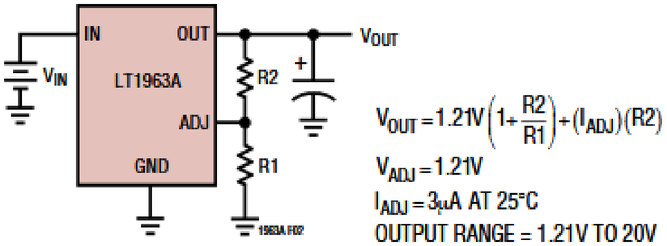

Figure 4-3: Adjustable Operation of the LT1963A [17]

The resistive divider values can be solved by using the Vout equation given in Figure 4-3. Table 4-1 shows the values chosen for the resistive divider to achieve the desired output voltages. For this divider, the value of R1 is chosen to be 1kΩ for all output voltages.

Table 4-1: Resistive Divider Values

V_{out}	R_2
1.5V	243Ω
3.3V	1.74kΩ
5V	3.16kΩ
9V	6.49kΩ
12V	8.87kΩ

4.3 Tracking Pre-Regulator Design

The goal of the tracking pre-regulator circuit is to minimize the voltage drop across the linear regulator to reduce losses. This can be accomplished by creating a circuit that creates a feedback voltage by looking at the input and output of the linear regulator. The following circuit can accomplish this.

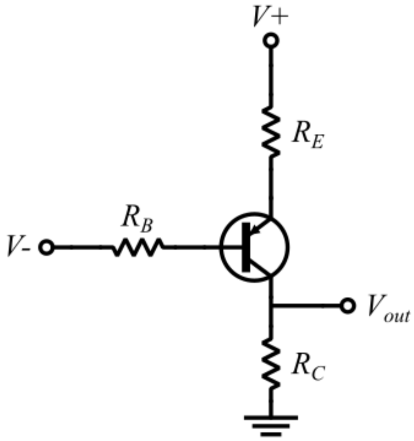

Figure 4-4: Tracking Pre-Regulator Circuit Schematic

In this circuit, the emitter current is approximately equal to the collector current. The current flowing through the emitter is determined by the difference between V^+ and V^-. The base voltage is approximately equal to V-. Therefore, the collector current can be calculated as shown.

$$I_C = I_E = \frac{V^+ - (V^- + V_{BE})}{R_E}$$

The output voltage of the circuit is created by the collector resistor.

$$V_{out} = I_C R_C$$

The V^+ is connected to the buck regulator output and the V^- is connected to the linear regulator's output. The output is connected to the feedback pin of the buck controller. Because the LT1963A requires a minimum input voltage of 1.9V, the difference between V^+ and V^- will be set to 1.9V. If an emitter resistor of 10kΩ is chosen and a base-emitter voltage of 0.7V is assumed, a collector current of 120µA can be generated.

$$I_C = \frac{1.9V - 0.7V}{10k\Omega} = 120\mu A$$

Since the feedback voltage of the LT3971A is 1.192V, selecting a R_C of 10kΩ generates a feedback voltage of about 1.2V, which is within 1% tolerance of the buck regulator's feedback voltage. Using this feedback network, the voltage across the linear regulator will be approximately 1.9V for all output voltages.

4.4 Simulation Results

The first goal of the simulation is to verify that the circuit operates as expected and quickly reaches steady state operation. Then, the simulation data will be used to compare the effect of including the pre-tracking regulator circuit by simulating the operation of a switching regulator and linear regulator cascade with and without the tracking circuit.

4.4.1 Operation and Transient Response

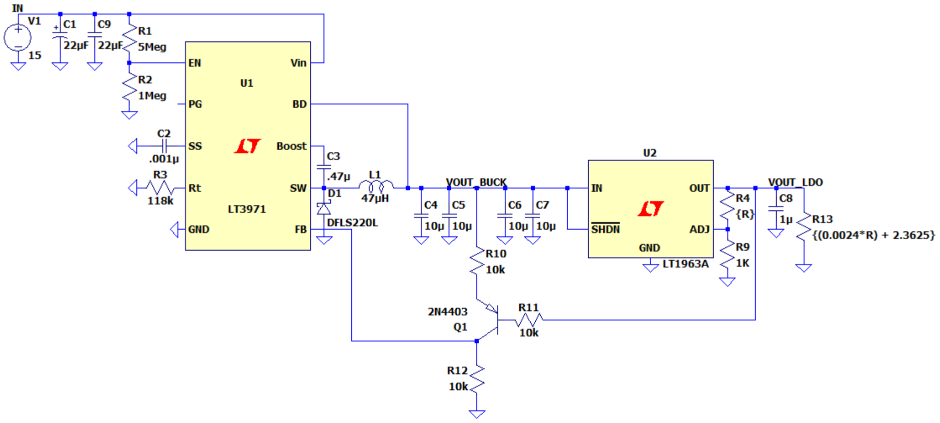

Figure 4-5: Regulator with the Feedback System in LTSpice

The circuit shown in Figure 4-5 is simulated in LTSpice for output voltages of 1.5V, 3.3V, 5V, 9V, and 12V. The plots in Figure 4-6 and 4-7 show the transient response of the buck output voltage and linear regulator output voltage.

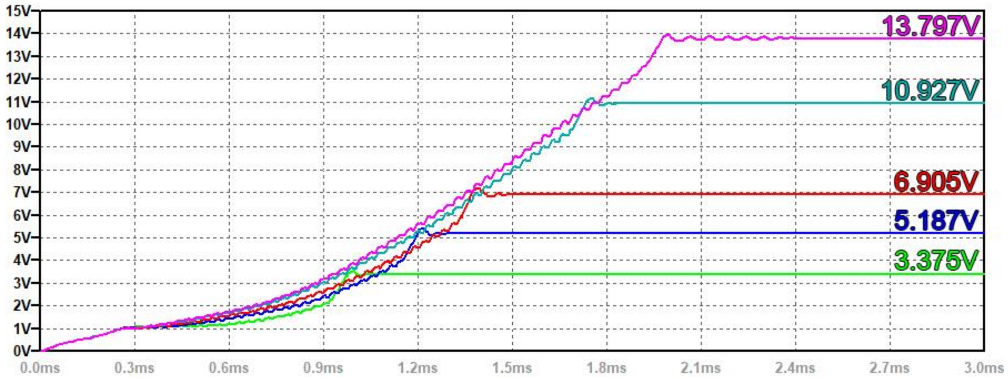

Figure 4-6: Transient Switching Regulator Output Voltage

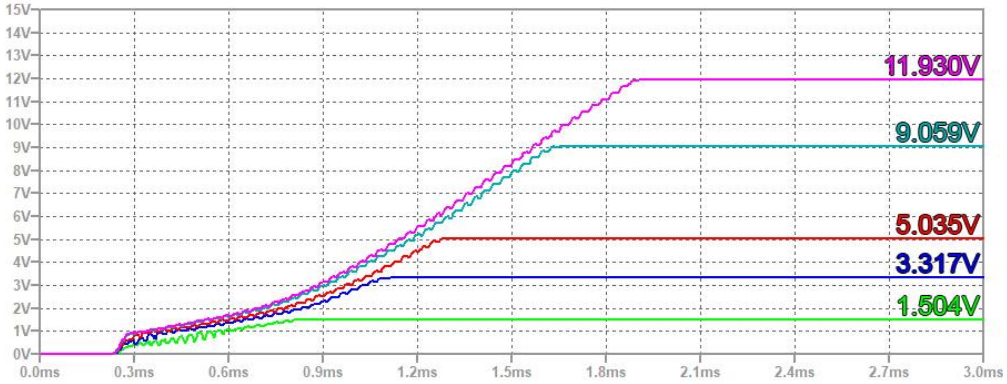

Figure 4-7: Transient Linear Regulator Output Voltage

The simulations function as expected. For all cases, the regulator achieves steady state 2ms after startup. The output voltage of the switching regulator is also closely following the linear regulator output voltage, showing the tracking circuit keeps a linear regulator voltage difference of 1.87V.

4.4.2 Comparisons to a Regulator without the Feedback Network

For comparison, the circuit is kept entirely the same except the feedback network is removed. The buck controller’s resistive divider is set to generate a buck output voltage of 12.5V to be slightly higher than the linear regulators highest output voltage of 12V. The non-regulated circuit is shown in Figure 4-8.

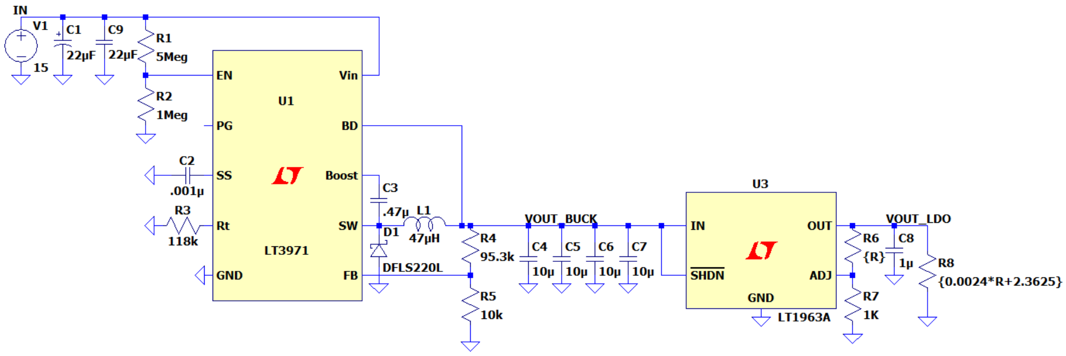

Figure 4-8: Regulator without the Feedback System in LTSpice

For both circuits, the efficiency of the entire regulator and power loss from the linear regulator is observed and shown below for output voltages of 1.5V, 3.3V, 5V, 9V, and 12V with an output current of 500mA.

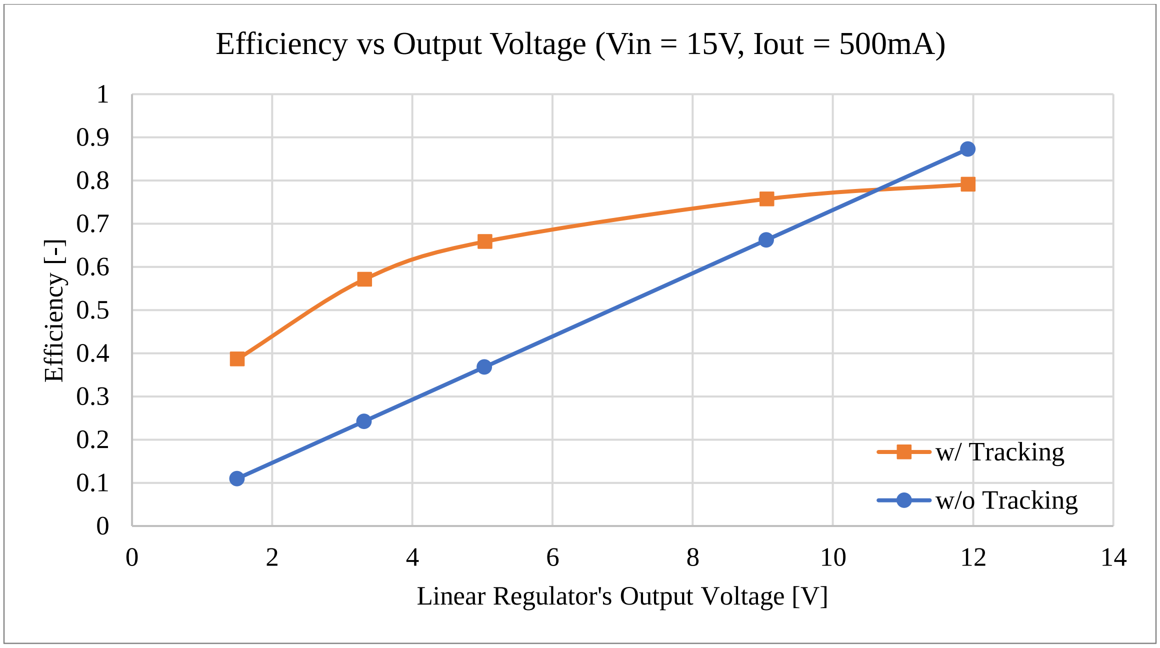

Figure 4-9: Output Voltage Effect of Tracking Regulator on Efficiency

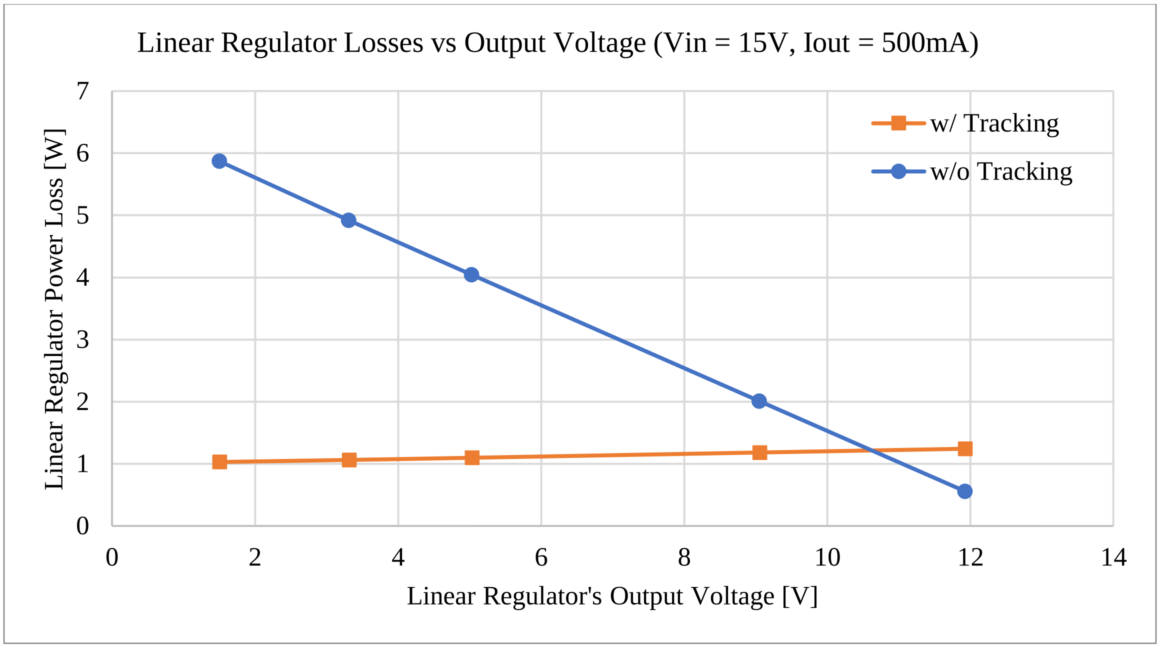

Figure 4-10: Output Voltage Effect of Tracking Regulator on Linear Regulator Losses

The break-even point for both efficiency and linear regulator losses of both boards is at about 10.6V. This makes sense as the converter without tracking has a switching converter output of about 12.5V. The difference between these two voltages is 1.9V, which approximately equal to the voltage difference created by the pre-tracking regulator. The converter with pre-tracking holds this voltage difference constant for all output voltages, whereas the converter with normal feedback will have a larger voltage difference when its output is lower than 10.6V and a higher voltage difference when its output is higher than 10.6V. This linear regulator voltage difference is directly related to the efficiency and power loss of the converter. The converter with tracking is shown to be more efficient when the output voltage is less than 10.6V, while the converter without tracking is more efficient when the output voltage is above 10.6V. With tracking, the linear regulator's power loss increases very slightly with increasing the output voltage.

Without tracking, linear regulator losses are much higher the lower the output voltage is. Therefore, in cases where multiple output voltages are not necessary, the tracking regulator would be ineffective at reducing losses.

Next, efficiency and power loss are observed with a changing output current. For this case, output voltages of 1.5V, 5V, and 12V are chosen while varying the output current to 100mA, 250mA, and 500mA.

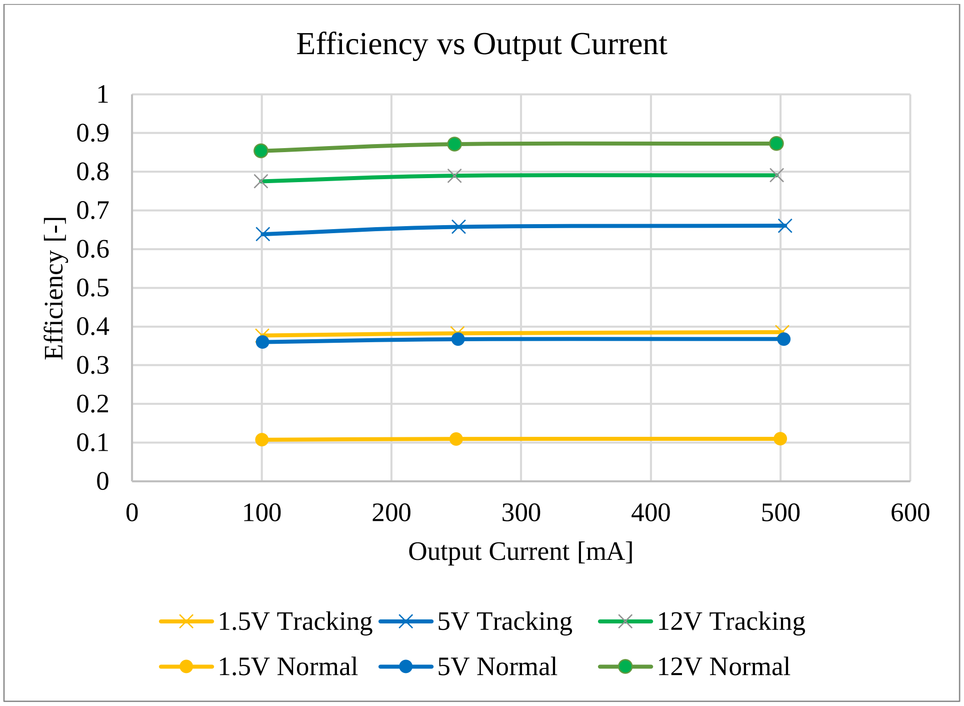

Figure 4-11: Output Current Effect of Tracking Regulator on Efficiency

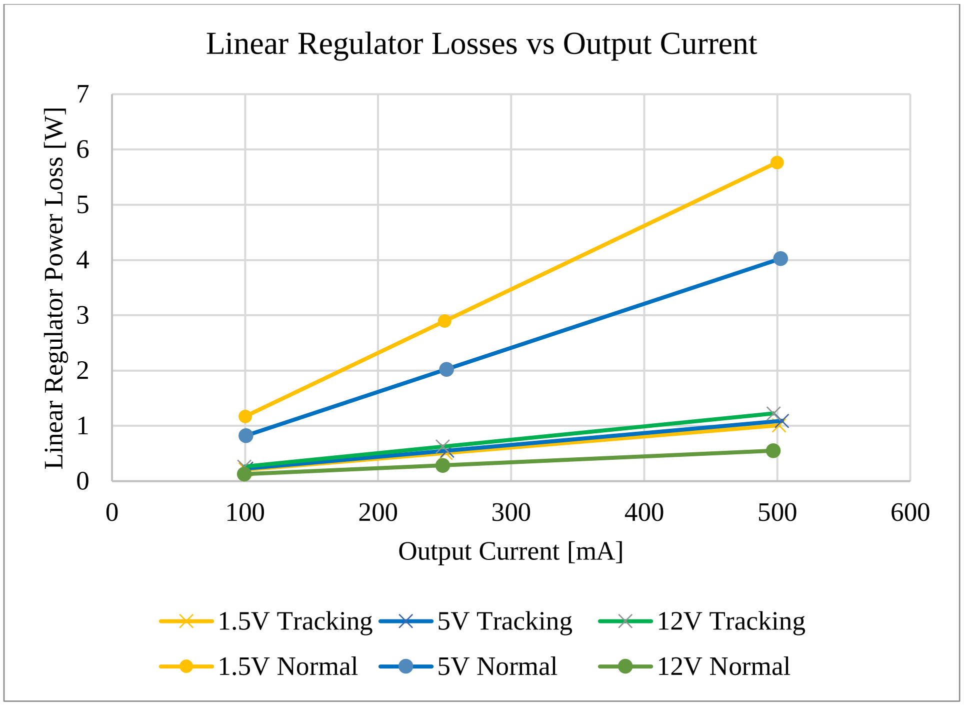

Figure 4-12: Output Current Effect of Tracking Regulator on Linear Regulator Losses

Again, the tracking regulator is most effective at reducing losses when the output voltage is lower. The power loss across the linear regulator is a function of the voltage difference across it and the output current, so losses increase linearly with increasing output current as expected.

4.5 Summary of Simulation Results

Simulation results of the converter with and without the feedback network verify the overall effectiveness of the pre-tracking regulator circuit. Observing the power loss of the linear regulator and efficiency confirmed that losses are generally lowered with pre-tracking regulator circuit. When using a switching regulator followed by a linear regulator, the pre-tracking regulator circuitry helps maintain a constant voltage difference across the linear regulator for all output levels, which causes the linear regulator power loss to only be a function of the output current. Simulation results further verify the initial component sizing is successful in achieving the desired operation of the converter; thus, will be used in the hardware construction and implementation of the converter.

Chapter 5. Hardware Design and Results

The next step is to test the differences between a converter that uses normal feedback and one that uses the pre-tracking regulator. To accomplish this, two separate boards were assembled, one for each case. On each board, the efficiency of the entire converter and the power loss of the linear regulator were measured.

5.1 Board Assembly

Proper board layout of a converter is vital to its operation. To achieve good operation along with lower electromagnetic interference (EMI), current loops must be kept as small as possible. Keeping sensitive traces small and placing ground traces around them such as the FB and RT pins of the controller helps to shield these nodes from the effects of switching. The switching ground and the linear regulator ground are connected through small traces to keep switching noise from coupling to the output. Physical separation between the switching and linear regulator also helps reduce switching noise coupling to the output. The output has a jumper J1 to achieve output voltages of 1.5V, 3.3V, 5V, 9V, and 12V. Test points TP1 and TP2 are used to measure the switching regulator output voltage and the feedback voltage, respectively. The switching regulator output voltage allows us to know the input voltage to the linear regulator for calculating power loss. The feedback voltage allows for easier troubleshooting if necessary. Placing a PNP in the place of Q1 allows us to achieve the pre-tracking regulator. Removing Q1 and shorting the collector and emitter gives a converter with normal feedback. Thus, one board design supports both converters.

Figures 5-1 and 5-2 show the top and bottom layers of the PCB that was used for hardware testing. The PCB was designed in KiCad and was produced by OSH Park. Figures 5-3 and 5-4 show the 3D view of the front and back of the board.

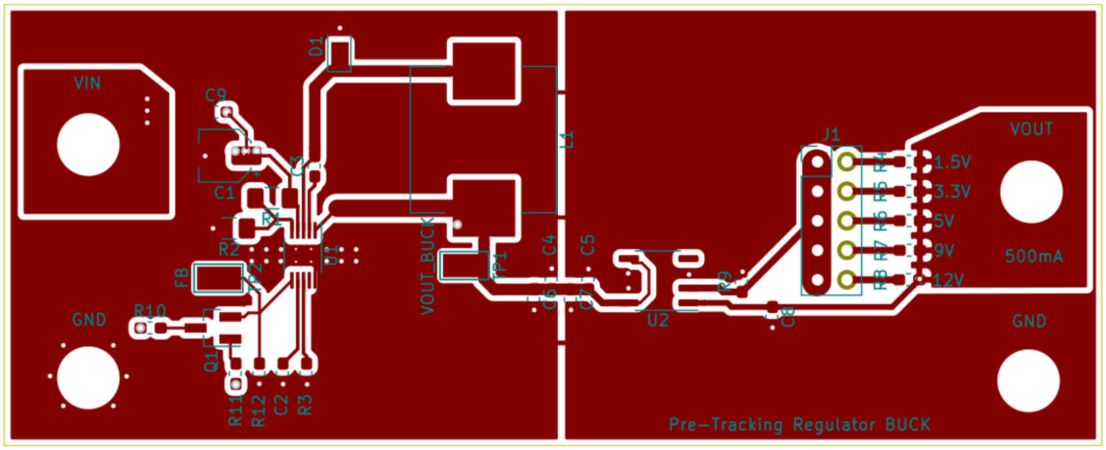

Figure 5-1: Top Layer of PCB

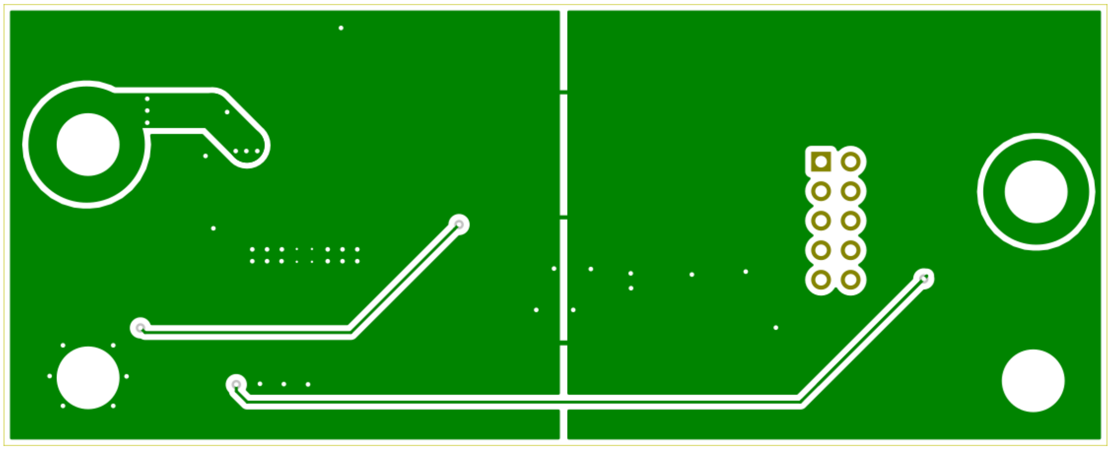

Figure 5-2: Bottom Layer of PCB

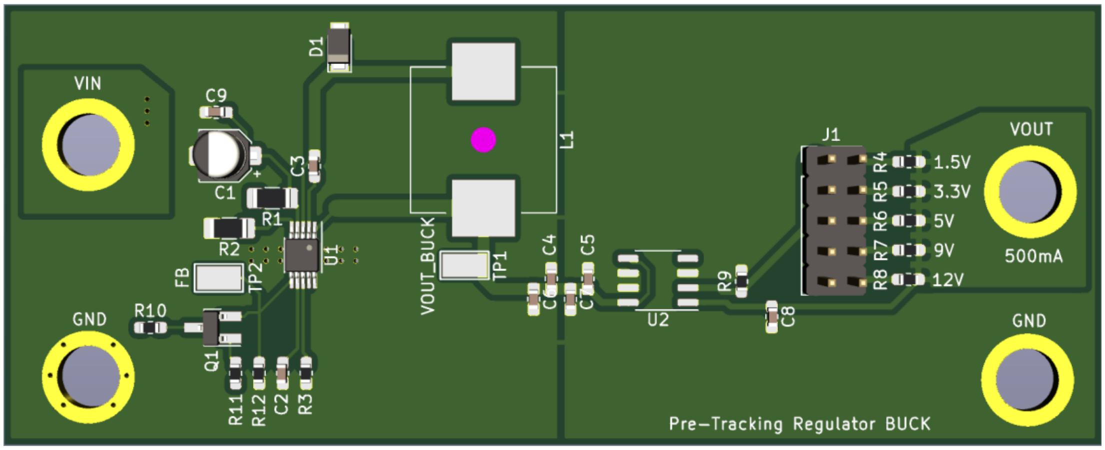

Figure 5-3: 3D View of Front of PCB

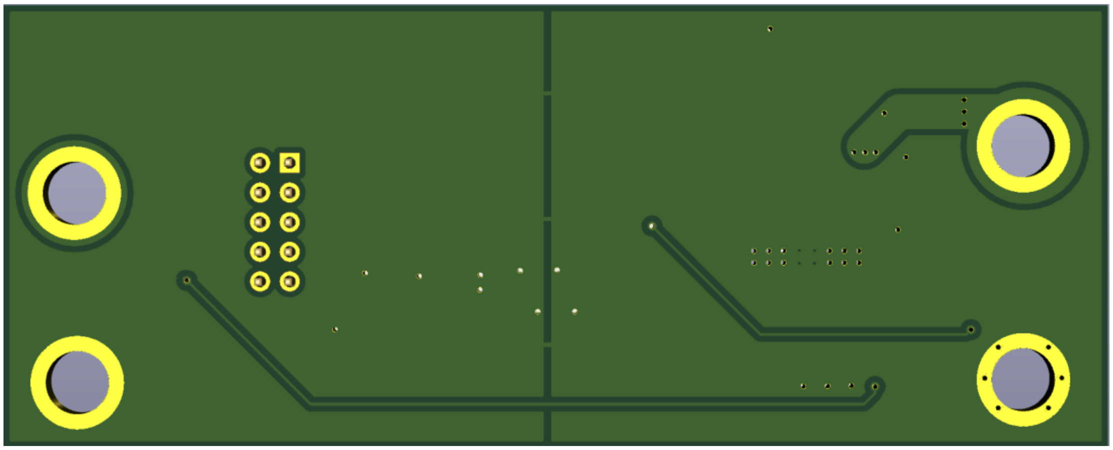

Figure 5-4: 3D View of Back of PCB

When physically soldering components onto the PCB, it was discovered that the orientation of Q1 was incorrect. The original PNP MMBT4403 was replaced with a 2N3906. The assembled board is shown in Figure 5-5.

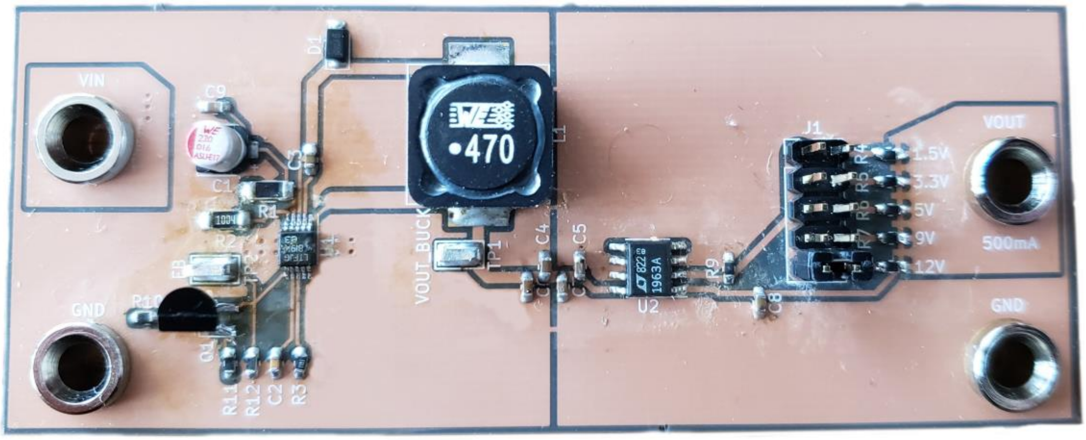

Figure 5-5: Converter Hardware with Pre-Tracking Regulator

To modify the board for normal feedback, R11 is removed, Q1 is removed and is shorted across the collector and emitter, and R10 is changed from 10kΩ to 95.3kΩ. These changes yield the test board shown in Figure 5-6.

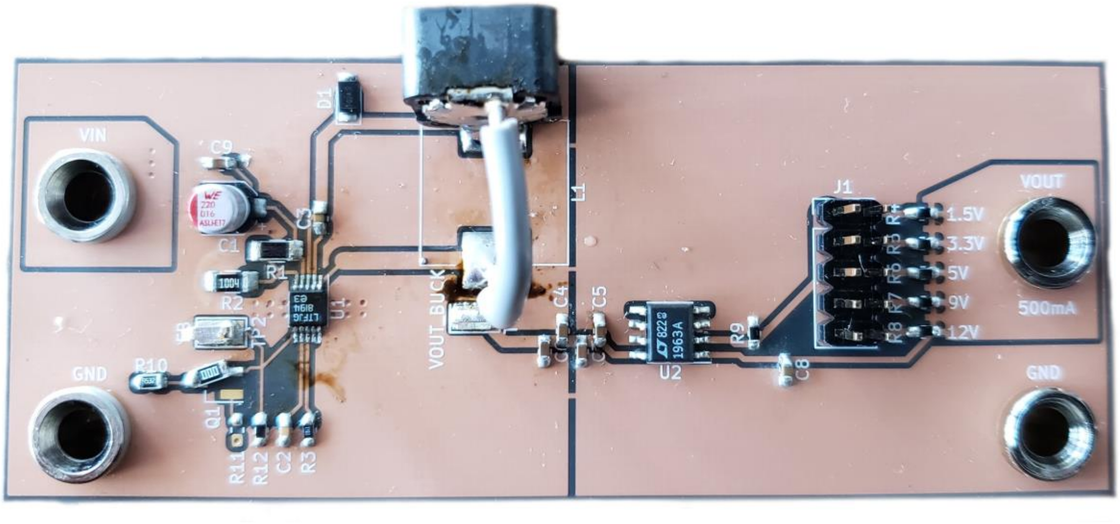

Figure 5-6: Converter Hardware with Normal Feedback

5.2 Test Configuration

Two tests are designed to evaluate the performance of the pre-tracking regulator board. Both tests use identical test set-ups. The Rigol DP832 Programmable DC Power Supplies provides the input power to the board and displays input current. The BK Precision 8540 DC electronic load is connected to the linear regulator’s output. Using multimeters to make measurements directly off the board gives more accurate readings than measuring values directly from the power supply or the electronic load due to line losses especially at high current. The Agilent Tech U3401A, Extech EX330, and BK Precision 5491A Digital Multimeters are used to measure the input voltage, switching regulator output voltage, and linear regulator output voltage, respectively. The lab test set-up is shown in Figure 5-7.

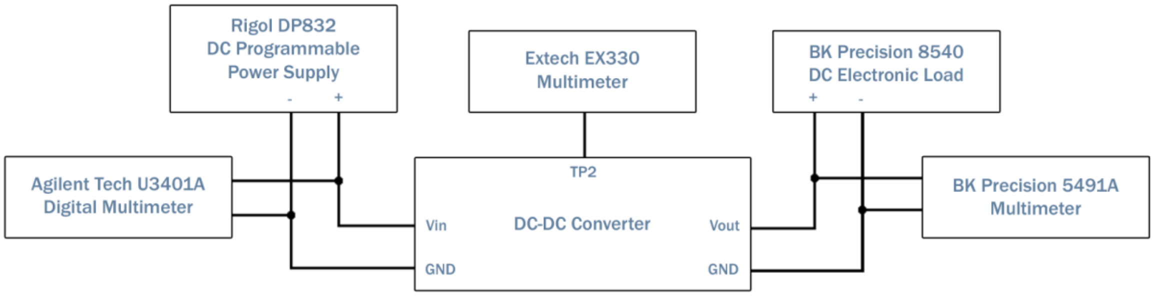

Figure 5-7: DC-DC Converter Test Configuration

5.2.1 Testing Pre-Tracking Regulator at Rated Load

The first test is to check the pre-tracking regulator board for efficiency and power loss across the linear regulator when running at rated load. The power supply is set to an input voltage of 15V and the DC electronic load is set to 500mA. The output voltage is varied, and the converter efficiency and linear regulator losses are measured for each setting.

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
14.992	0.14	2.099	3.39	1.5	0.499	1.890	0.943	0.748	35.67%
14.987	0.21	3.147	5.17	3.305	0.499	1.865	0.931	1.649	52.40%
14.984	0.27	4.046	6.84	5.017	0.499	1.823	0.909	2.504	61.89%
14.977	0.41	6.141	10.77	9.051	0.499	1.719	0.858	4.517	73.55%
14.972	0.5	7.486	13.37	11.974	0.499	1.396	0.697	5.975	79.81%

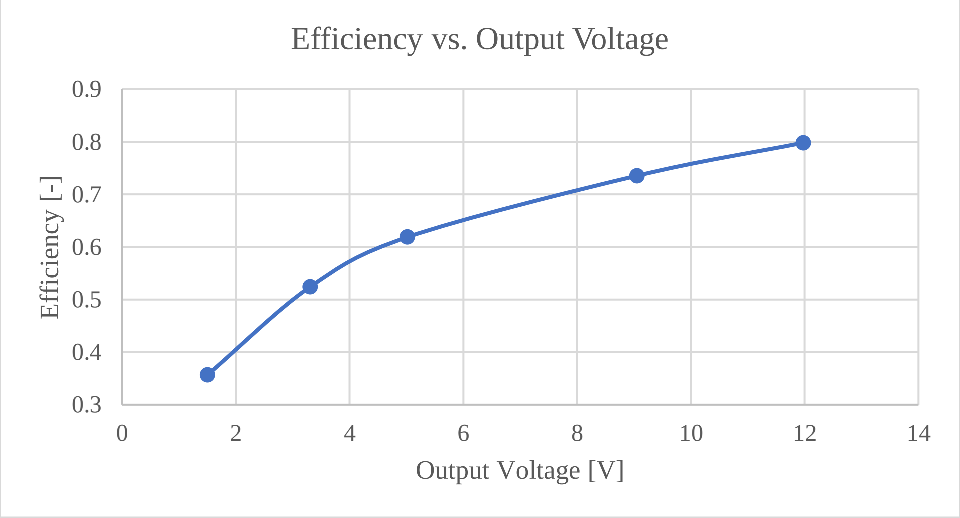

Figure 5-8: Hardware Data of Efficiency vs Output Voltage with Tracking

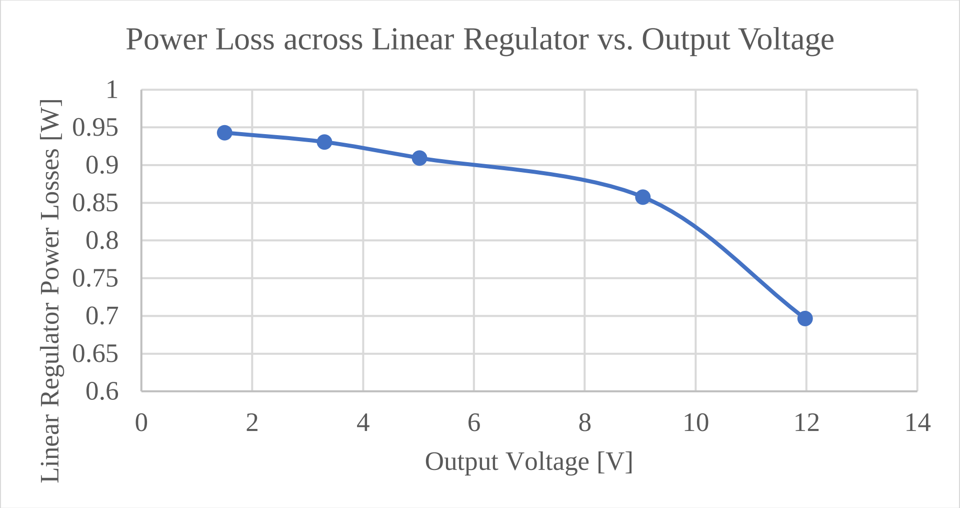

Figure 5-9: Hardware Data of Linear Regulator Losses vs Output Voltage with Tracking

The hardware data closely follow the simulation data shown in Figures 4-9 and 4-10. Efficiency data parallel that of our simulation with about 40% efficiency at an output voltage of 1.5V and about 80% efficiency at an output voltage of 12V. The relationship between linear regulator losses and output voltage is not as linear as those obtained from simulations. This is due to the voltage across the linear regulator not being constant.

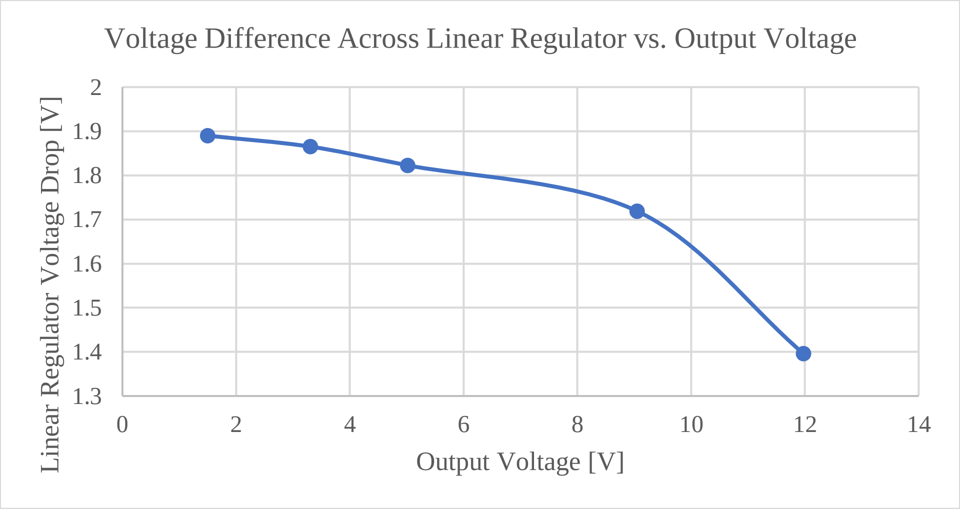

Figure 5-10: Linear Regulator Voltage Difference vs Output Voltage with Tracking

At full load, the voltage difference across the linear regulator experiences a drop of about 0.5V as the output voltage is increased. This is unlike the case at the 200mA load shown later in Chapter 5.2.2 where the relationship is relatively constant which agrees with the expected result. The discrepancy may potentially be caused by the higher EMI noise due to the larger current. This increased level EMI noise effect is one thing that will not be shown by the simulation results.

Currently, the PNP in the pre-tracking regulator may be acting as an antenna for radiated emissions. This transistor being directly attached to the feedback pin of the buck converter and radiated emissions may cause the controller to see a higher output voltage, resulting in a decrease in duty cycle. Decreasing duty cycle causes a lower buck converter output voltage. If the higher output current and voltages cause higher radiated emissions on the feedback pin of the buck controller, the buck converter's output voltage may be lower than expected.

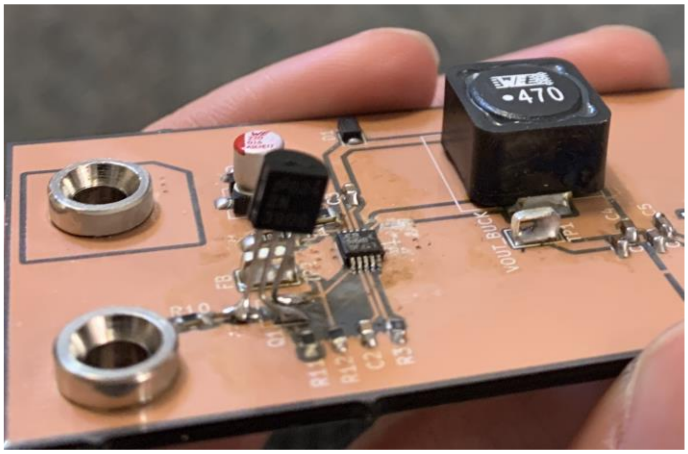

Figure 5-11: Standing PNP Potentially Capturing Radiated Electromagnetic Interference

5.2.2 Testing Pre-Tracking Regulator and Normal Feedback Performance

The second test is to compare both the pre-tracking regulator board and the normal feedback board for efficiency, losses, and load regulation when varying the load current. Unlike the board with pre-tracking, the board with normal feedback enters thermal shutdown when running at the rated load. The thermal resistance of the LT1963A in the SO-8 package is 55°C/W. At worst case when the output voltage is set to 1.5V, if the input voltage to the linear regulator is assumed to be 12.5V and ambient temperature is assumed to be 20°C, the expected junction temperature can be calculated as follows:

$$P_D = (12.5V - 1.5V)(500mA) = 5.5W$$

$$T_{J,LDO} = (5.5W * 55℃/W) + 20℃ = 322.5℃$$

When running the board at 1.5V and rated load, the linear regulator goes into thermal shutdown with temperatures of 126.6°C. Therefore, the rated load must be reduced to have a fair comparison between the two boards. First, the output voltage is swept and the DC electronic load is set to 200mA. Efficiency and linear regulator losses are measured and recorded in Table 5-2.

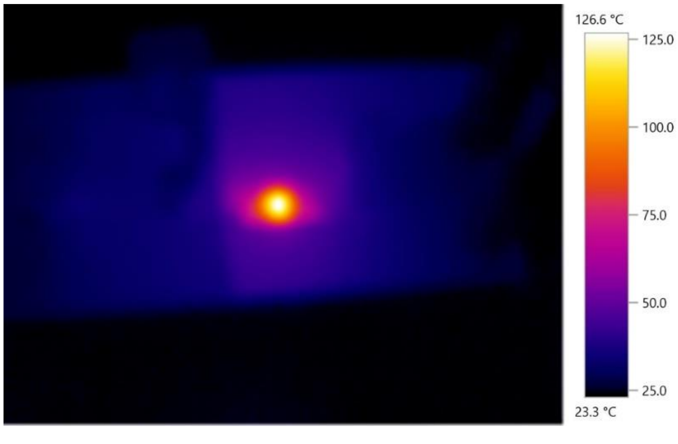

Figure 5-12: Thermal Image of Board with Normal Feedback at 1.5V and 500mA

Table 5-2: Hardware at 200mA Output 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)	$P_{D, LDO}$ (W)	P_{OUT} (W)	η
Tracking	14.997	0.06	0.899	3.317	1.505	0.2	0.362	0.301	33.46%
	14.996	0.09	1.345	5.11	3.318	0.2	0.358	0.664	49.17%
	14.994	0.11	1.649	6.83	5.039	0.2	0.358	1.008	61.10%
	14.991	0.17	2.548	10.85	9.087	0.2	0.353	1.817	71.32%
	14.989	0.21	3.147	13.7	12.016	0.2	0.337	2.403	76.35%
No Tracking	14.990	0.19	2.848	12.47	1.476	0.2	2.199	0.295	10.36%
	14.990	0.19	2.848	12.47	3.245	0.2	1.845	0.649	22.78%
	14.990	0.19	2.848	12.48	4.938	0.2	1.508	0.988	34.68%
	14.990	0.19	2.848	12.45	8.957	0.2	0.699	1.791	62.90%
	14.990	0.19	2.848	12.44	11.831	0.2	0.122	2.366	83.08%

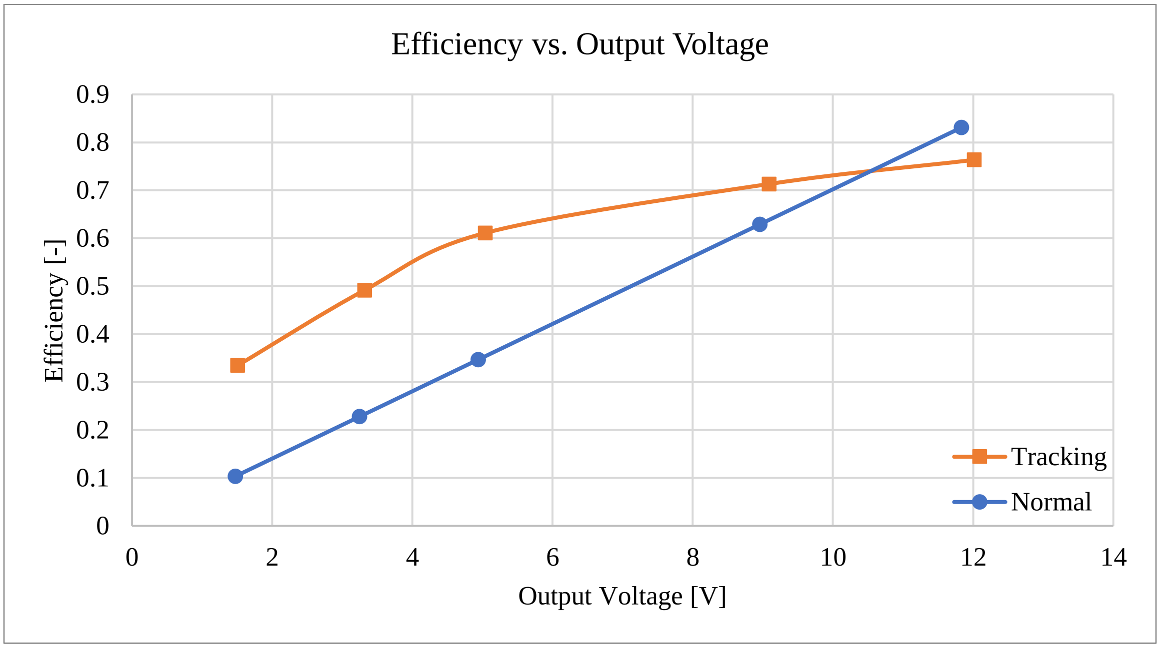

Figure 5-13: Hardware Data of Efficiency vs. Output Voltage at 200mA

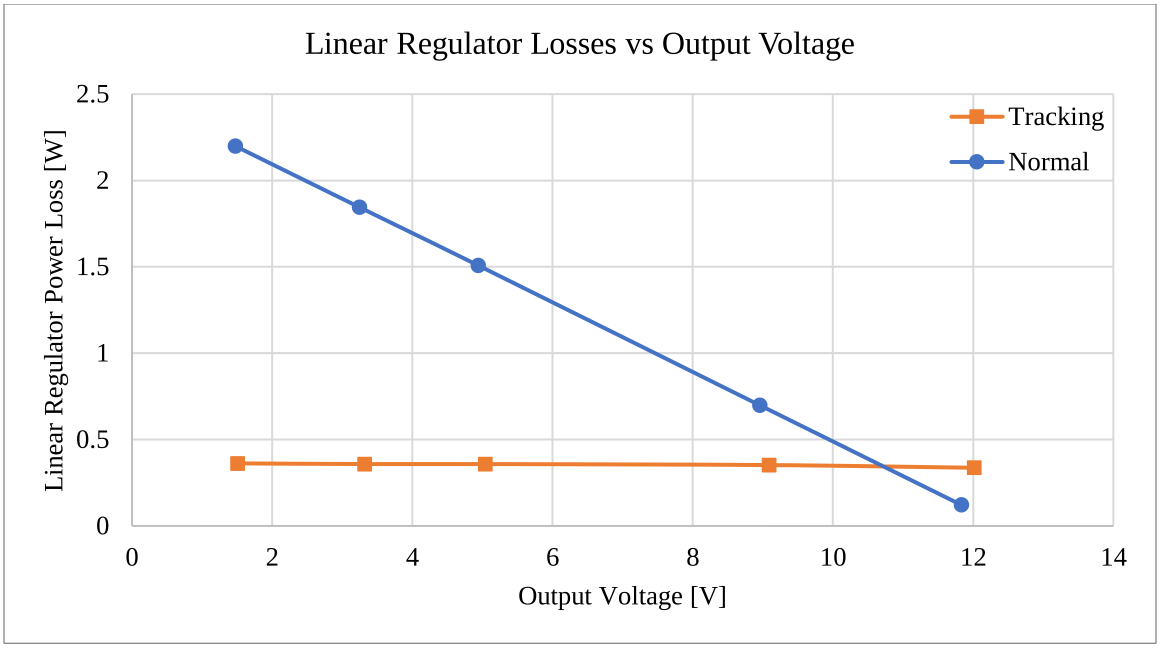

Figure 5-14: Hardware Data of Linear Regulator Losses vs. Output Voltage at 200mA

Like the simulation data, the regulator with pre-tracking yields the more efficient results of the two boards when the output voltage is less than 10.5V and is less efficient when the output is greater than 10.5V. The linear regulator losses are almost the same at all voltages when tracking is implemented. Without the tracking, the linear regulator losses are inversely proportional to output voltage. Moreover, efficiency and linear regulator losses are measured while sweeping output current for output voltages of 1.5V, 5V, and 12V. The output currents chosen for this test are 50mA, 100mA, and 150mA.

Table 5-3: Hardware at 200mA Output DC Characteristics at Varying Output Currents

	V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	$V_{OUT, BUCK}$ (V)	$V_{OUT, LDO}$ (V)	I_{OUT} (A)	$P_{D, LDO}$ (W)	P_{OUT} (W)	η
Tracking	15	0.02	0.30	3.32	1.508	0.05	0.091	0.075	25.14%
	15	0.03	0.45	3.319	1.508	0.1	0.181	0.151	33.50%
	14.998	0.04	0.60	3.318	1.507	0.15	0.272	0.226	37.68%
	14.999	0.03	0.45	6.81	5.050	0.05	0.088	0.253	56.12%
	14.998	0.06	0.90	6.81	5.047	0.1	0.176	0.505	56.09%
	14.996	0.08	1.20	6.81	5.044	0.15	0.265	0.757	63.07%
	14.998	0.06	0.90	13.75	12.040	0.05	0.085	0.602	66.90%
	14.995	0.11	1.65	13.74	12.033	0.1	0.171	1.203	72.95%
	14.992	0.16	2.40	13.72	12.026	0.15	0.254	1.804	75.20%
No Tracking	14.997	0.06	0.90	12.44	1.492	0.05	0.547	0.075	8.29%
	14.995	0.1	1.50	12.44	1.487	0.1	1.095	0.149	9.92%
	14.993	0.15	2.25	12.44	1.480	0.15	1.644	0.222	9.87%
	14.997	0.06	0.90	12.44	4.983	0.05	0.373	0.249	27.69%
	14.995	0.1	1.50	12.44	4.971	0.1	0.747	0.497	33.15%
	14.993	0.15	2.25	12.43	4.962	0.15	1.120	0.744	33.09%
	14.997	0.06	0.9	12.44	11.855	0.05	0.029	0.593	65.87%
	14.995	0.1	1.50	12.44	11.851	0.1	0.059	1.185	79.03%
	14.993	0.15	2.25	12.43	11.846	0.15	0.088	1.777	79.01%

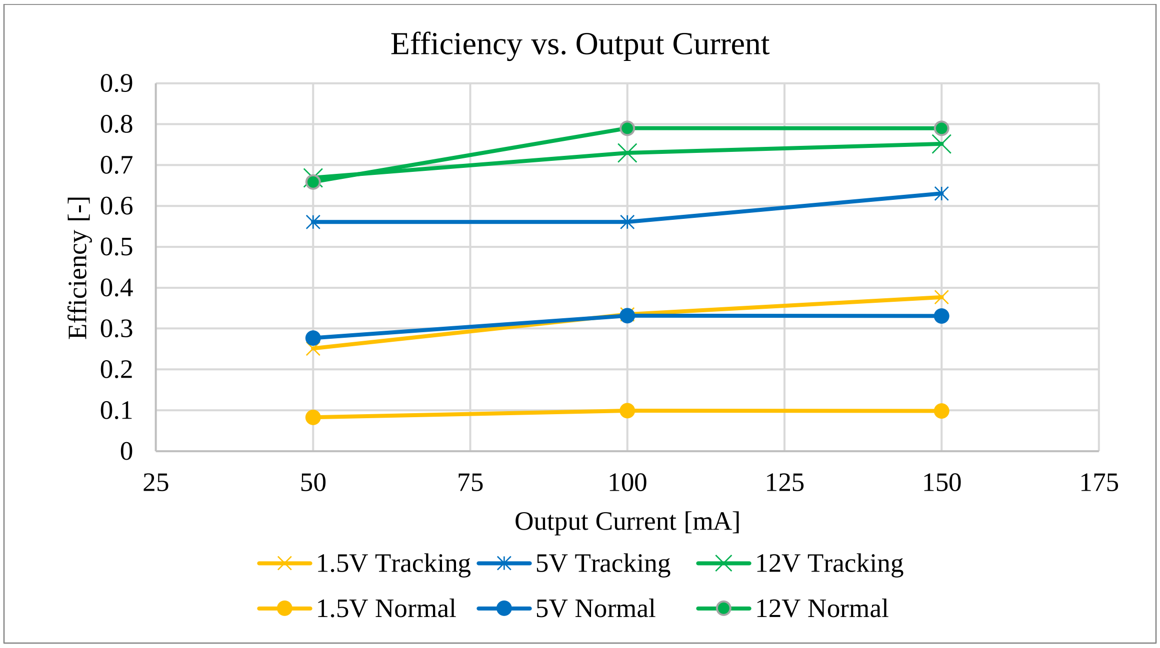

Figure 5-15: Hardware Data of Efficiency vs. Output Current

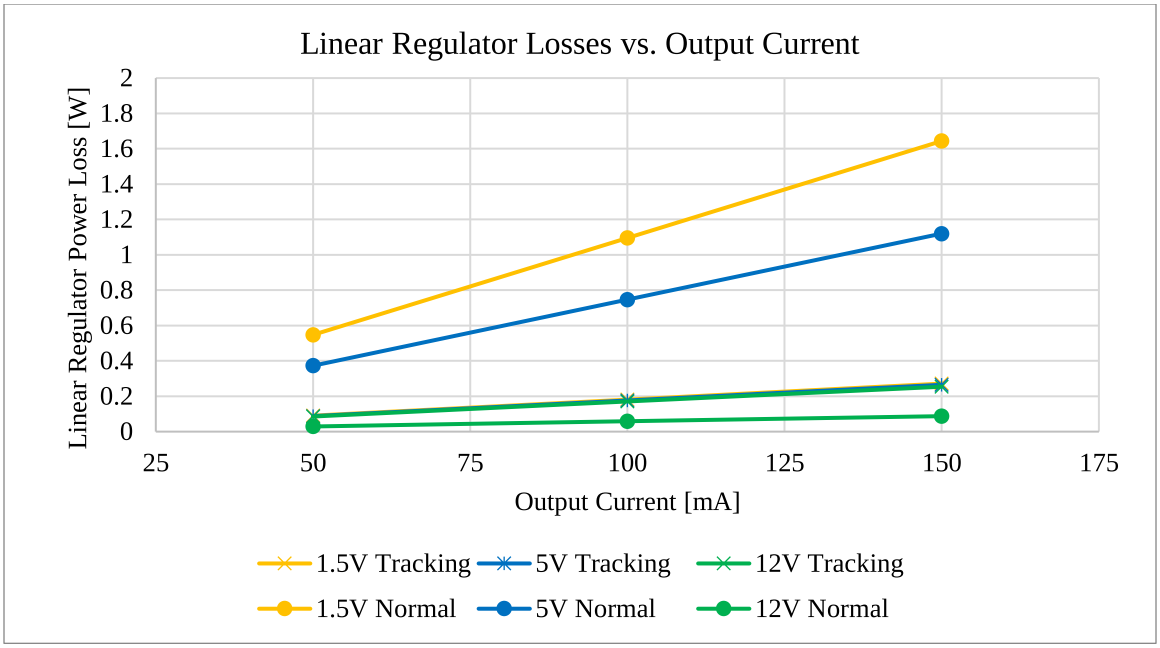

Figure 5-16: Hardware Data of Linear Regulator Losses vs. Output Current

Sweeping the output current shows a slight increase in efficiency with increasing output current in the range of 7% to 13%. Data shows that the most efficient case is running the board with normal feedback at an output voltage of 12V, achieving efficiencies from 66% to 79%. All cases using the board with tracking follow, and the remaining cases using normal feedback are the least efficient. Linear regulator losses are also linearly increasing with respect to output current as expected. Losses are the same for all cases that use the pre-tracking regulator.

Load regulation can then be found for both converters to see if the pre-tracking regulator has any effect. For a fair comparison, full load will be 200mA and light load will be 50mA. Output voltages will be set to 1.5V, 5V, and 12V.

Table 5-4: Hardware Load Regulation Comparison

	V_{OUT} Setting	**V_{OUT} w/ I_{OUT} = 50mA**	**V_{OUT} w/ I_{OUT} = 200mA**	**Load Regulation**
Tracking	1.5	1.508	1.505	0.199%
	5	5.050	5.039	0.218%
	12	12.040	12.012	0.233%
No Tracking	1.5	1.492	1.476	1.072%
	5	4.983	4.938	0.903%
	12	11.855	11.831	0.202%

The hardware results generally agree with the trends seen in simulation data, with the exception of operating the converters at rated load seen in Chapter 5.2.1. Both simulation and hardware achieved efficiencies of approximately 40% to 80% and experienced constant linear regulator losses with varying output voltage.

The pre-tracking regulator has promise in low-power, noise sensitive, and variable output applications. At full load of 500mA, the pre-tracking regulator helps keep the power dissipated by the linear regulator to lower than 0.95W for all output voltages and helps prevent thermal shutdown. Lower power dissipation allows for smaller heatsinks to be used. At 200mA, the converter with pre-tracking yields higher efficiencies than the converter with normal feedback when the output voltage is lower than 10.5V, with a difference of at most 23% efficiency at an output voltage of 1.5V. At an output voltage of 12V, the converter with normal feedback is more efficient by 6%. Load regulation measurements for the converter with pre-tracking exhibit more stable performance with about 0.22%, while the converter with normal feedback ranges from 0.2% to 1% depending on output voltage, with lower output voltages resulting in worse load regulation.

Chapter 6. Conclusion

Implementation of the pre-tracking regulator on a cascaded linear regulator demonstrates a significant increase in efficiency when an application requires a wide range of output voltages, such as a variable power supply. This project reduces the power loss of the linear regulator in a variable output cascaded DC-DC converter by maintaining a voltage difference across the linear regulator when changing the output voltage.

Simulations in LTSpice allowed for converter design verification and prediction of converter performance. Hardware testing and results reflected and overall agree with the simulation data. Variations in data can be attributed to non-idealities of components and board layout. Furthermore, these differences can also be the result of parasitic capacitances and inductances, electromagnetic interference, and thermal behavior.

The technical requirements set for the converter's design were overall met. These include the operation of the proposed design at 15V input voltage while outputting 1.5V, 3.3V, 5V, 9V, and 12V and delivering a full load of 500mA. The efficiency of the system ranges from 35% at the output voltage of 1.5V, and increases with higher output voltages, achieving an efficiency of 80% at 12V output voltage.

The hardware results indicate areas for improvement. A more efficient system could be achieved by increasing the collector resistor or decreasing the emitter resistor of the pre-tracking regulator after start-up. Once in steady-state operation, these resistors can be changed to drop the difference across the linear regulator. Both changes would decrease the output voltage of the switching converter, resulting in a lower voltage difference across the linear regulator and lower losses. This could be incorporated is by using a digital potentiometer to change resistances after start-up. This would result in lower losses and higher efficiency of the system.

Fixing the board's layout may also help the issues as explained in Chapter 5.2.1. Due to the misplacement of Q1's pads, a substitute thru-hole PNP was used for testing. This leaves the feedback pin of the switching converter to be vulnerable to electromagnetic interference. Further testing will be needed to investigate this loss behavior.

The proposed pre-tracking regulator demonstrated its ability to have the switching converter's output follow the linear regulator's output to improve the overall regulator's efficiency. Efficiency of the converter with the pre-tracking regulator shows a range of 33% to 76% compared to a converter with normal feedback with a range of 10% to 83%. This solution finds its most effective use when a low-noise DC-DC conversion to various output voltages is necessary. In situations where only a single output voltage with low-noise is needed, it is more effective to design a cascaded converter with normal feedback, where the switching regulator is set to have an output voltage very close to the linear regulator's output.

Overall, this project provides a proof of concept for a new feedback network in a switching regulator to linear regulator cascaded DC-DC converter that will improve overall efficiency of the converter under varying output voltage condition. Test results of the hardware prototype show that linear regulator losses are reduced especially at lower output voltages, resulting in a more efficient system and lower thermal design requirements than the converter without the tracking circuit.

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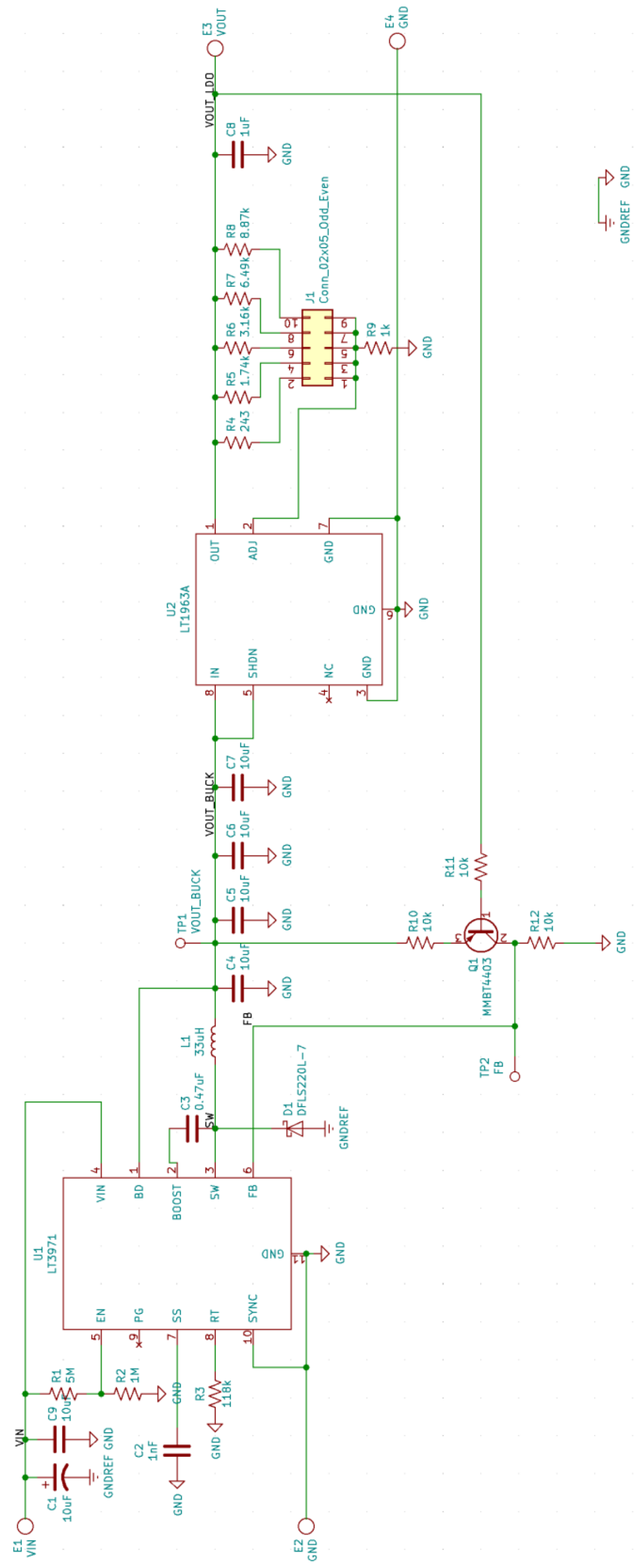
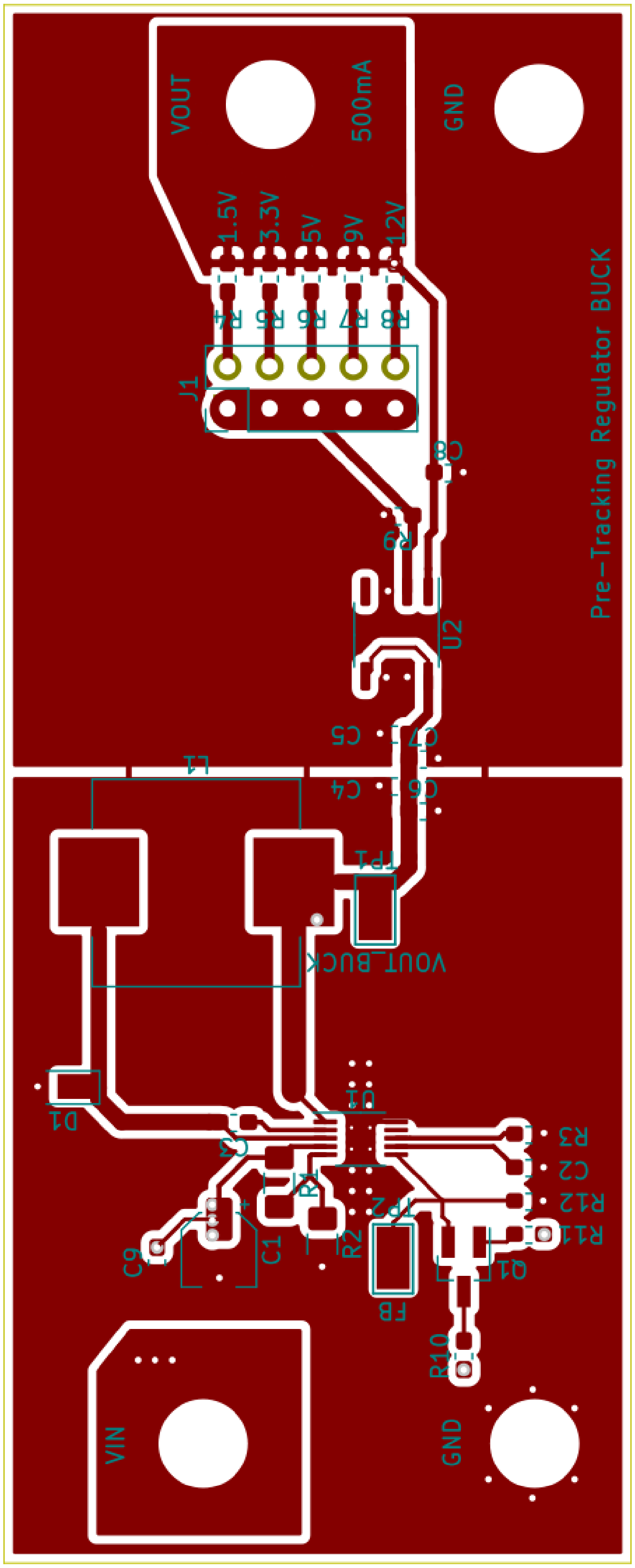
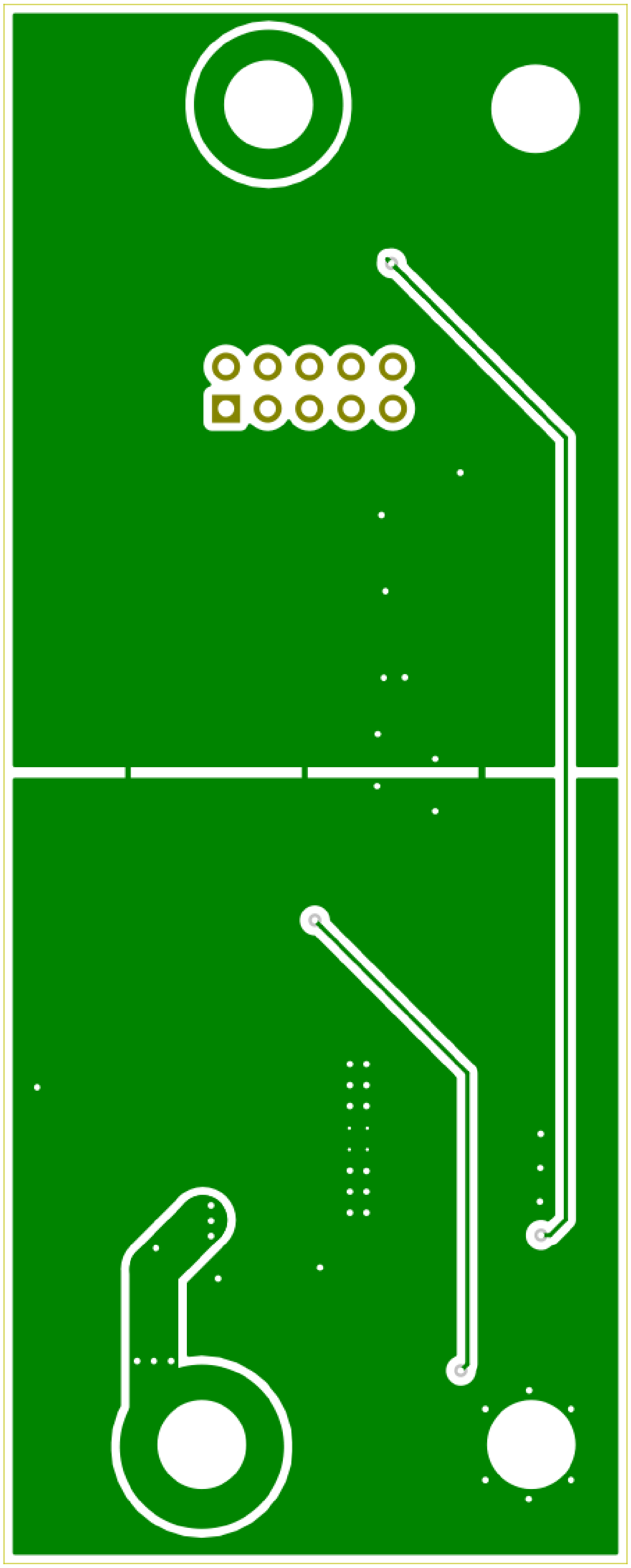
APPENDIX A: KiCAD Schematic



APPENDIX B: KiCAD Top PCB Layer



APPENDIX C: KiCAD Bottom PCB Layer



APPENDIX D: Bill of Materials

Reference Des.	Description	Quantity	Manufacturer	Part Number
C1	Aluminum Electrolytic Capacitors - SMD WCAP-ASLI 10uF 16V 20% SMD/SMT	1	Würth Elektronik	865080340003
C2	Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 1000pF 0603 10% 16V MLCC	1	Würth Elektronik	885012206034
C3	Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 0.47uF 0603 10% 16V MLCC	1	Würth Elektronik	885012206050
C4, C5, C6, C7	Multilayer Ceramic Capacitors MLCC - SMD/SMT 0603 10uF 16volts X5R 10%	4	Würth Elektronik	GRM188R61C106KAALD
C8	Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 1uF 0603 10% 16V MLCC	1	Würth Elektronik	885012206052
C9	Multilayer Ceramic Capacitors MLCC - SMD/SMT 0805 22uF 20% 16VDC X5R	1	Murata	GRM219R61C226ME15K
D1	Schottky Diodes & Rectifiers 2.0A 20V LFF	1	Diodes Inc.	DFLS220L-7
L1	Fixed Inductors WE-PD 1280 47uH 2.7A .1Ohm	1	Würth Elektronik	744770147
Q1	Bipolar Transistors - BJT 600mA 40V PNP	1	ON Semi	MMBT4403LT1G
R1	Thin Film Resistors 1/4W 5MOhm 0.1% AEC Q200 Qualified	1	Susumu	RG3216P-5004-B-T1
R2	Thick Film Resistors 1/4Watt 1Mohms 1% Commercial Use	1	Vishay / Dale	CRCW12061M00FKEAC
R3	Thick Film Resistors 1/10watt 118Kohms 1%	1	Vishay / Dale	CRCW0603118KFKEA
R4	Thick Film Resistors 1/10watt 243ohms 1%	1	Vishay / Dale	CRCW0603243RFKEA
R5	Thick Film Resistors 1/10watt 1.74Kohms 1%	1	Vishay / Dale	CRCW06031K74FKEA
R6	Thick Film Resistors 1/10watt 3.16Kohms 1%	1	Vishay / Dale	CRCW06033K16FKEA
R7	Thick Film Resistors 1/10watt 6.49Kohms 1%	1	Vishay / Dale	CRCW06036K49FKEA
R8	Thick Film Resistors 1/10watt 8.87Kohms1% 1%	1	Vishay / Dale	CRCW06038K87FKEA
R9	Thick Film Resistors 1/10watt 1.0Kohms 1%	1	Vishay / Dale	CRCW06031K00FKEA
R10, R11, R12	Thick Film Resistors 1/10watt 10Kohms 1%	3	Vishay / Dale	CRCW060310K0FKEA
U1	IC REG BUCK ADJ 1.2A 10MSOP	1	Linear Technologies / Analog Devices	LT3971EMSE#PBF
U2	LDO Voltage Regulators Fast Transient 1.5A LDO	1	Linear Technologies / Analog Devices	LT1963AES8#PBF
J1	CONN HEADER VERT 10POS 2.54MM	1	Würth Elektronik	61301021121
----	JUMPER W/TEST PNT 1X2PINS 2.54MM	1	Würth Elektronik	60900213421
E1, E2, E3, E4	Test Plugs & Test Jacks NON-INSUL JACK .218" BRASS NICKEL PLTD	4	Keystone Electronics	575-4
TP1, TP2	Circuit Board Hardware - PCB TEST POINT	2	Keystone Electronics	5019