Current Tracking Power Supply for Sensor Calibration

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I. INTRODUCTION

Sensors are commercially available in a wide variety, such as level sensors, temperature sensors, accelerometers, pressure sensors, as well as many others. Within each sensor category, the sensor can be effectively used for a large array of different applications. Sensors are used to provide vital information about a system, which will determine its performance or its function. While sensors can be incredibly useful tools, if calibrated insufficiently, sensors can provide false information or cause a system to work improperly. From this aspect, it can be seen that sensors are only useful if properly calibrated.

During the calibration process, a reference voltage is used to set the initial measurement, usually at rest (such as room temperature in a temperature sensor). If the reference voltage is inconsistent, it could lead to sensors reading improper values. Likewise, if the current exceeds the absolute maximum specifications of the sensor, it can lead to damage to the sensor. In order to circumvent some of the necessities for very consistent voltage supply, calibration can be done using a process called ratiometric measurement using an analog to digital converter. In ratiometric measurement, the measured voltage used for calibration is based on a ratio of two reference voltages to a single excitation voltage rather than a single reference. Using a resistive bridge, the analog to digital converter sets its positive reference to the voltage supply and sets its negative reference to ground, while measuring the potential values across the resistors between the bridge. In this configuration, the sensor resistor is independent from the original voltage reference, but is rather dependent on the ratio of the two reference voltages to the original reference voltage. An example of ratiometric measurement using an analog to digital converter is shown below in Figure 1.1.

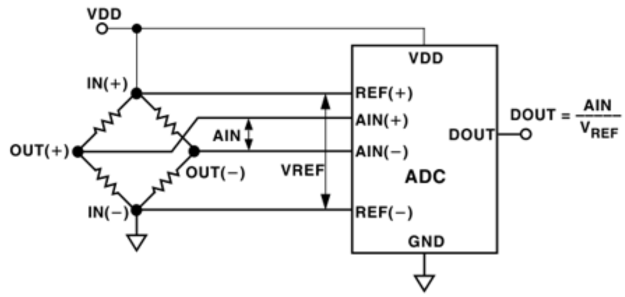


Figure 1.1: Ratiometric Measurement Using an Analog to Digital Converter

While ratiometric measurement allows for greater variation of voltage supply, calibration is still dependent on an excitation voltage or voltage reference. If the voltage reference varies while the ratio to the voltage reference stays the same, it can still cause the output to vary. Therefore, it is important for the voltage supply to be as steady as possible to prevent calibration errors.

Kavlico, a sensor design company based out of Moorpark, CA, has asked to design a power supply for their new Kaveen USB Programmer box. The USB Box is used to communicate with, calibrate and program the Kaveen Application-Specific Integrated Circuits (ASICs) within each sensor sold by Kavlico. In order to accurately calibrate each individual sensor, the USB Programmer Box requires a precise power supply in order to supply the sensor with constant voltage and current that does not drift over time. Without a consistent, reliable power supply, the sensors accuracy cannot be dependable.

II. BACKGROUND

The power supply in current design of the Kaveen USB Programmer box meets a variety of important specification. First and foremost, the supply is able to provide consistent, accurate voltage supply, with less than 1mV drop across V_{SUPPLY} at 25mA. Each supply has over-current protection, can be turned on separately with a 3.3V signal and can be reset by being powered off and then on again. Likewise, the current tracking has both span and offset adjustments. The previous system tracks current by translating current to voltage, then reading its value through an Analog to Digital Converter (ADC).

However, the current design is not without its drawbacks. While the circuit is highly configurable, in that it is able to change voltage tracking, current tracking, offset and span values by changing the components, it is overly complicated and takes up far too much space on Printed Circuit Boards, taking up roughly 29cm^2 (6.3cm x 4.6cm). The current design utilizes 0-5V ADC for its current tracking, while the new USB Boxes utilize 0-10V ADCs. In its current form, current is tracked by translating current to voltage, which is then sent to an ADC, which in turn is sent again to a microcontroller. The translation process of Current-to-ADC-to-Microcontroller can be simplified, which will leave smaller room for error when debugging or trying to isolate problems in the USB Box. Most importantly, the current tracking on the current USB Box can drift over extended periods of time. This drift can be caused by excessive chip and component heating and layout.

In this respect, the new power supply that Kavlico is looking for corrects the negative drawbacks caused by the old power supply design while still maintaining its previous design specifications. This can be accomplished in a wide variety of ways, utilizing ADCs, Digital to Analog Converters (DACs), Microcontrollers, Integrated Circuits (ICs) and other analog components. Because the design can be achieved with such variety, Kavlico has asked to make multiple designs, highlight each design’s positives and negatives, and then make a suggestion on the best plan of action, keeping in mind certain considerations, such as board space of design, design simplicity, cost of design and efficiency of design.

III. REQUIREMENTS

The design of the power supply is subject to certain constraints. Like the original supply, it must be able to provide consistent, accurate supply voltage, supplying 5V at 4mA and 20mA with less than 1mV drop across V_{SUPPLY} at 25mA, as their current design is able to provide. Likewise, it must provide over-current protection, in order to prevent damage to the connected sensor or power supply circuit. The supply must remain off until it receives either an external 3.3V or an external 5V signal, which are the available signals within the USB Box that are used to turn on the supply. When turned off and on again, the power supply should reset and resume its original operation, which would allow the power supply to recover from user errors, which would cause the USB Programmer Box to enter a shut down mode. The power supply should be able to track current supplied with minimal amounts of drift over time and be able to communicate current tracking to either a microcontroller (preferably Atmel, as the rest of the Kaveen USB Programmer Box utilizes Atmel chips) or utilize 0-10V ADC, which is utilized within the new USB Boxes. Lastly, the power supply must be protected from improper loads (i.e., shorting the output), in order to prevent damage to the power supply circuitry.

Because the requirements can be accomplished in several different ways, each design should be concluded with certain considerations. For each design, the total cost should be recorded. Likewise, comments should be made on its layout, simplicity and the amount of board space the design will take up, which would ideally be less than the current design. Likewise, while the power supply is designed for 5V output, considerations should be made for an additional 15V output, as the Kaveen USB Programmer Box uses both a 5V and 15V supply for sensor calibration.

IV. DESIGN AND CONSTRUCTION

The power supply design must be able to accurately provide 5V out at 4mA and 20mA loads, be able to track current to a microcontroller or a 0-10V ADC, and shut down if the load draws too much current. Likewise, the power supply should be able to be turned on using an external 3.3V or 5V signal. In this respect, the design can be broken into two separate sections: Constant voltage supply and current tracking with shutdown circuitry.

4.1 Constant Voltage Supply Design

The ability to accurately supply 5V at 4mA and 20mA is the most important aspect of the power supply design. There are several different topologies that provide for constant voltage supply. The two topologies that were chosen based on reliability and performance were Low Dropout (LDO) Linear Voltage Regulators and DC-DC Step-Down (Buck) Controllers. Both topologies have their respective strengths and drawbacks, which will be highlighted below in their respective sections. After choosing these topologies, several chips were then analyzed to assess their performance.

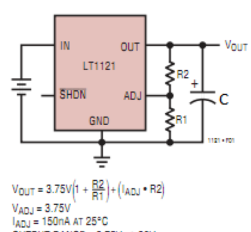
4.1.1 Low Dropout Linear Voltage Regulators

Low Dropout (LDO) Linear Voltage Regulators are a type of voltage regulator that can operate with minimal input-output differential voltage (called dropout). LDO regulators usually consist of a power Field Effect Transistor (FET) and a differential amplifier with a set reference. By setting external resistors in the feedback path of the output and the differential amplifier, the output voltage is regulated to a specific level set by the reference of the differential amplifier. Low Dropout

Regulators usually have an input capacitor to protect the IC from voltage spikes from turning on the input, a resistive divider with a trimming potentiometer to set the output voltage, and an output capacitor to provide output stability and prevent the output from oscillating. This section will contain the chosen linear regulator circuits that will be analyzed and tested for their performance within the power supply. Most of the chips appear very similar externally with slight differences, but may exhibit different performance over the desired load range.

4.1.1.1 LT1121 – Micropower Low Dropout Regulator with Shutdown

The LT1121 is a basic Low Dropout Linear regulator that is designed to operate from up to 30V on the input and regulate to an adjustable 3.75V to 30V. The LT1121 is able to carry load currents up to 150mA, which meets the specifications as described in the Requirements section above. This regulator is also able to enter a "shutdown" state by driving its shutdown pin lower than 0.25V. While in shutdown, the device has a quiescent input current of approximately 16uA. Because the voltage regulator is simple in its design, it requires only an input capacitor, an output capacitor and variable resistive divider. In its simplicity, it will likely take up a very small amount of board space. Unfortunately, the regulator does not have embedded current limiting and does not track the output current, so this must be done externally through a separate circuit, as further detailed below. The circuit diagram for the LT1121 is shown below in Figure 4.1.

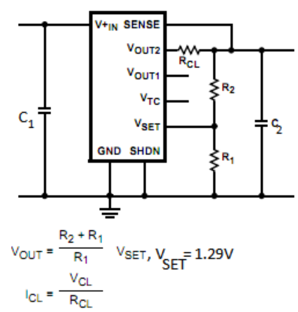


Component	Value
R_1	100kΩ
R_2	32.4kΩ
C	1µF

Figure 4.1: LT1121 Circuit with Component Values for 5V Output Operation

4.1.1.2 ICL7663S – Programmable Micropower Voltage Regulator

The ICL7663S Programmable Micropower Voltage Regulator is designed to operate from 1.6V to 16V on the input and regulate to 1.3V to 16V output. The ICL7663S is designed to carry a maximum load current of 40mA and has embedded overcurrent protection by setting an external current limiting resistor. Much like the LT1121, the ICL7663S is designed for minimal external components, which will likely take up smaller amounts of board space than other regulator designs. Likewise, the ICL7663S features an active-high shutdown pin, causing the chip to enter “shutdown” when the shutdown pin receives a voltage higher than 1.4V. In shutdown, the regulator turns off the output and draws only 10uA quiescent current. The circuit diagram for the ICL7663S is shown below in Figure 4.2.

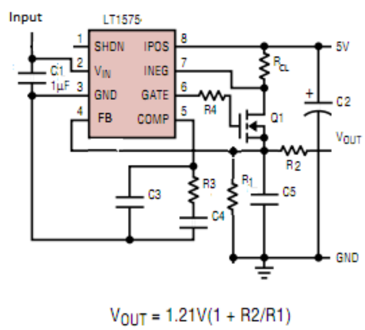


Component	Value
R_1	26.1kΩ
R_2	75kΩ
R_{CL}	16.9Ω
C_1	.047µF
C_2	10µF

Figure 4.2: ICL7663S Circuit with Component Values for 5V Output Operation with 30mA Current Limit

4.1.1.3 LT1575 – Ultrafast Transient Response, Low Dropout Regulator

The LT1575 Ultrafast Low Dropout Regulator is designed to operate from up to 22V on the input and regulate to an adjustable 1.5V to 15V output. Much like the ICL7663S, the LT1575 is designed to carry a maximum load current of 40mA and has embedded overcurrent protection by setting an external current limiting resistor. Much like the other ICs, this linear regulator has a shutdown pin that is active high, causing the chip to enter shutdown when the shutdown pin receives a voltage higher than 1.24V. The LT1575 regulator is also highly customizable, allowing the designer to set a timer latch-off, which allows the chip to reset after a certain period of time that is set by an additional capacitor. Unfortunately, because this IC is particularly complex, it also features a large number of external components, consisting of an external transistor, five external capacitors, and several resistors. In addition to numerous external components, the circuit also requires two separate supplies: one for the input voltage pin and one for the current sense input pin. The circuit diagram for the LT1575 is shown below in Figure 4.3.

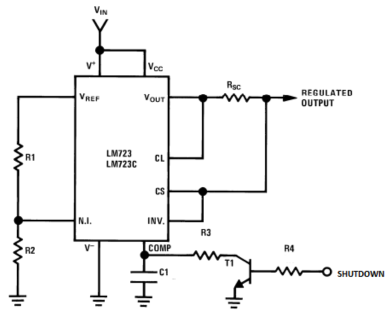


Component	Value
R_1	26.1kΩ
R_2	75kΩ
R_{CL}	16.9Ω
R_3	7.5kΩ
R_4	5Ω
C_1	1µF
C_2	220µF
C_3	10pF
C_4	1000pF
C_5	24µF

Figure 4.3: LT1575 Circuit with Component Values for 5V Output Operation with 30mA Current Limit

4.1.1.4 LM723 – High Precision Voltage Regulator with Current Limit

The LM723 High Precision Regulator is designed to operate from up to 40V on the input and regulate to an adjustable 2V to 37V output. The LM723 is capable of delivering up to 150mA of load current. Unfortunately, the LM723 does not have an embedded shutdown pin; however the chip can still shut down from an external signal through the use of an external NPN transistor. Driving the base of the NPN transistor high causes the LM723 to turn off its output. Unlike the other linear regulators, the LM723 is only available in a 14 pin package rather than an 8 pin package, causing the overall circuit to take up more board space. The circuit diagram for the LM723 is shown below in Figure 4.4.



$I_{LIMIT} = \frac{V_{SENSE}}{R_{SC}}$, $V_{SENSE} = 0.65V$

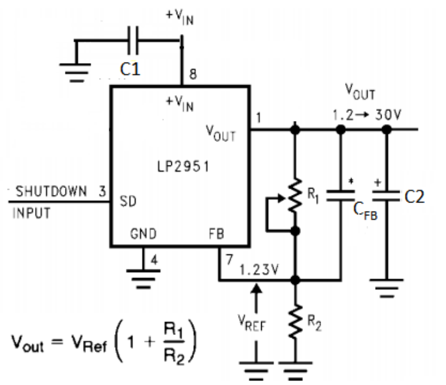
$V_{OUT} = \left(V_{REF} \times \frac{R2}{R1 + R2}\right)$, $V_{REF} = 7.15V$

Component	Value
R_1	750Ω
R_2	2.2kΩ
R_{SC}	21.5Ω
R_3	2kΩ
R_4	2kΩ
C_1	1µF

Figure 4.4: LM723 Circuit with Component Values for 5V Output Operation with 30mA Current Limit

4.1.1.5 LP2951 – Micropower Low Dropout Voltage Regulator with Shutdown

The LP2951 Micropower Low Dropout Regulator is designed to operate from up to 30V on the input and regulate to an adjustable 1.25V to 29V output. The LM723 is capable of delivering up to 100mA of load current but does not have integrated current limiting or current tracking. Much like many of the other regulators, the LP2951 features a shutdown pin which allows the IC to enter shutdown mode when it receives a voltage higher than 2V on its shutdown pin. The LP2951 requires few external components and is cheaper than the other LDO Regulators by a significant margin. In this respect, the LP2951 will take up a small amount of board space and will be quite cheap. The circuit diagram for the LP2951 is shown below in Figure 4.5.



Component	Value
R_1	309kΩ
R_2	100kΩ
C_1	1uF
C_2	3.3µF
C_{FB}	0.01µF

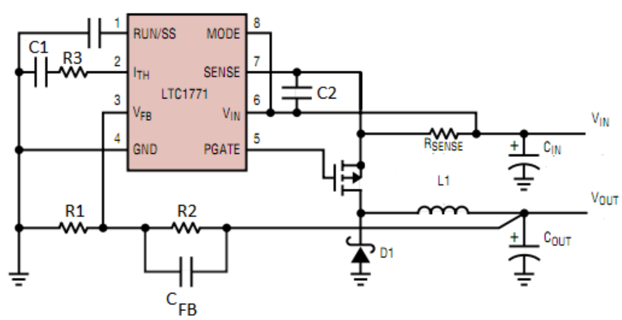
Figure 4.5: LP2951 Circuit with Component Values for 5V Output Operation

4.1.2 DC-DC Step-Down (Buck) Controllers

DC-DC Controllers are a type of switching voltage regulator that is used to change an input level of DC to different output level. In the case of a Step-Down (Buck) Converter, the input voltage is dropped to a lower output voltage. Some of the benefits of using DC-DC converters are that they are usually more efficient in the terms of power and they are able to drive several amps of current to the load. Unfortunately, with the nature of the project only requiring approximately 30mA to the load and efficiency not being the main concern of the supply, using a DC-DC controller may be unnecessary for the given supply. Likewise, due to the nature of DC-DC controllers being a switching regulator as well as utilizing larger inductors and capacitors, lots of noise can be generated in the form of Electromagnetic Interference (EMI). In this respect, the design of DC-DC Converters must be very careful in both component placement within the converter and placement of the converter itself, such that interference does not impact the performance of either the converter or other portions of the Kaveen USB Calibration Box. This section will contain the chosen DC-DC Step-Down Controllers that will be analyzed and tested for their performance within the power supply.

4.1.2.1 LTC1771 – High Efficiency, Step Down DC-DC Controller

The LTC1771 High Efficiency Step Down DC-DC Controller is designed to operate from up to 20V on the input and regulate to an adjustable 1.23V to 18V output. The LTC1771 is capable of very high efficiency (above 93%); however this higher efficiency is only seen at higher loads. This regulator also features a RUN/Shutdown pin, which allows the chip to be put in either the active on state (RUN) if the pin is open or taken high or in the shutdown state if the pin is grounded. While in shutdown, the supply is limited to 9uA of quiescent current. This chip is also able to set an output current limit through the selection of a sense resistor. The LTC1771 requires several external components and is subject to very specific design and component placement constraints, which will cause the converter to take up a larger amount of board space. The circuit diagram for the LTC1771 is shown below in Figure 4.6.



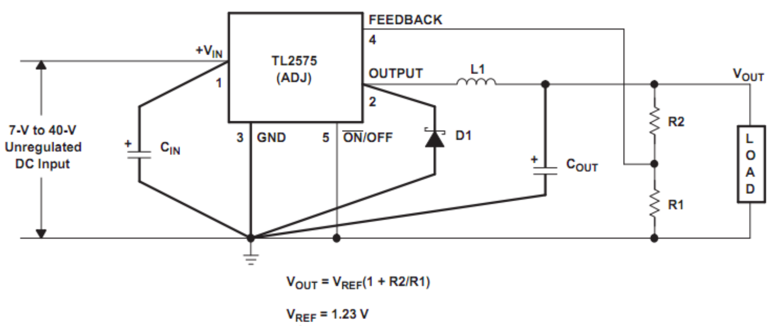
$$V_{OUT} = 1.23\left(1+\frac{R2}{R1}\right)$$

Component	Value
R_1	1MΩ
R_2	3.09MΩ
R_3	100kΩ
R_{SENSE}	3.32Ω
C_{IN}	33µF
C_{OUT}	150µF
C_{FB}	5pF
C_1	220pF
C_2	1000pF
L_1	22µH

Figure 4.6: LTC1771 Circuit with Component Values for 5V Output Operation with 30mA current Limit

4.1.2.2 TL2575 – 1A Simple High Efficiency Step-Down Switching Voltage Regulator

The TL2575 Simple High Efficiency Step Down DC-DC Controller is designed to operate from 4.75V to 40V on the input and regulate to an adjustable 1.23V to 37V output. Much like the LTC1771, the TL2575 is able to deliver a high efficiency at higher loads (above 93%); however the TL2575 requires much fewer external components. This regulator is able to operate with only an input capacitor, an output capacitor, a Schottky diode, an inductor and the resistive divider to adjust the output. In this respect, this converter will be smaller and have simpler design constraints to be followed for normal operation. In addition, the TL2575 utilizes an enable pin, which allows the supply to be shut down by driving the enable pin low. Unfortunately, the TL2575 does not have an integrated output current limit. The circuit diagram for the TL2575 is shown below in Figure 4.1.



Component	Value
R_1	2kΩ
R_2	6.12kΩ
C_{IN}	33µF
C_{OUT}	150µF
L_1	22µH

Figure 4.7: TL2575 Circuit with Component Values for 5V Output Operation

4.2 Current Tracking and External Shutdown Circuitry

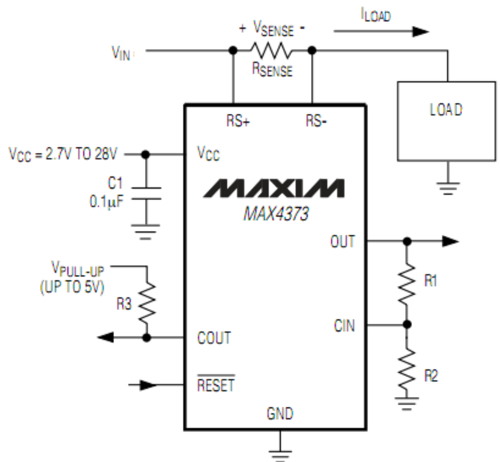
While constant voltage supply may be the heart of the power supply, the ability to track current is also incredibly important. The simplest and most cost effective way to track current is through the use of a Current-Sense Amplifier (CSA). A current sense amplifier measures the voltage potential across a sense resistor, and then amplifies this potential drop by a gain set by the current-sense amplifier. By choosing a known value for a sense resistor, you are able to determine the output voltage at particular current thresholds (such as 4mA, 20mA and overcurrent conditions) and send these voltages either a microcontroller or ADC. Likewise, these voltages can be utilized by a comparator to send an external signal to the constant voltage supply portion of the power supply in order to shut down the supply.

The supply must also be able to be turned off by an external 3.3V or 5V signal. By utilizing a pair of Single Pole, Double Toggle (SPDT) Analog switches, either a 5V digital signal or digital ground can be sent to the shutdown input of the power supply.

This section will contain the selected Current Sense Amplifiers that will be analyzed and tested for their performance within the power supply.

4.2.1 MAX4373H – Micropower, High Side Current Sense Amplifier, Comparator and Reference

The MAX4373H High Side Current Sense Amplifier is able to measure current across a sense resistor by measuring the voltage drop across the resistor, then multiplying it by a set gain of 100V/V and displaying the resulting voltage at the output pin. By setting an individual sense resistor, the MAX4373H is able to utilize the entire 0-10V output voltage range without the need for external, gain-setting resistors. Additionally, the MAX4373H contains a latching comparator with a reference. By using a resistive divider across the input to the comparator, when the current exceeds a desired level, such as 30mA, the comparator output latches to 5V, which can then be used to turn off the supply. By grounding the /RESET pin, the latch is reset, causing the comparator output to drop to 0V. By setting the sense resistor within the feedback path of the supply, the sense resistor does not cause the output to drop. Additionally, the MAX4373H is available in a small 8-pin µMax package, which takes up less board space than an 8-pin SOIC package. The MAX4373H is also available for alternative voltage gains, such as 20V/V for the MAX4373T and 50V/V for the MAX4373H. The circuit diagram for the MAX4373H is shown below in Figure 4.8.



$V_{OUT} = A_V*(R_{SENSE}*I_{LOAD})$, $A_V = 100V/V$

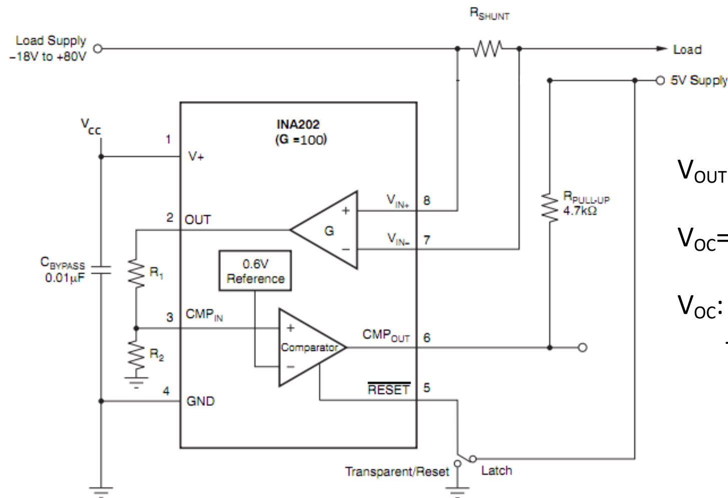
$V_{OC}=0.6*(1+R1/R2)$

V_{OC}: Output Voltage that causes C_{OUT} to go high

Figure 4.8: MAX4373H Circuit with Output Voltage and Overcurrent Equations

4.2.2 INA202 – High Side Current-Shunt Monitor with Comparator and Reference

The INA202 High Side Current-Shunt Monitor is able to measure current in the same way that the MAX4373H is able to measure current. The INA202 is very similar to the MAX4373H; the INA202 has a latching comparator with a reference that is able to latch to 5V when the output voltage meets a particular overcurrent threshold, and is available in an alternative package for a gain of 20V/V and 50V/V. In this respect, both chips should have very similar or identical performance, but the INA202 costs approximately half as much as the MAX4373H. The circuit diagram for the INA200 is shown below in Figure 4.9.



$V_{OUT} = A_V*(R_{SHUNT}*I_{LOAD})$, $A_V = 100V/V$

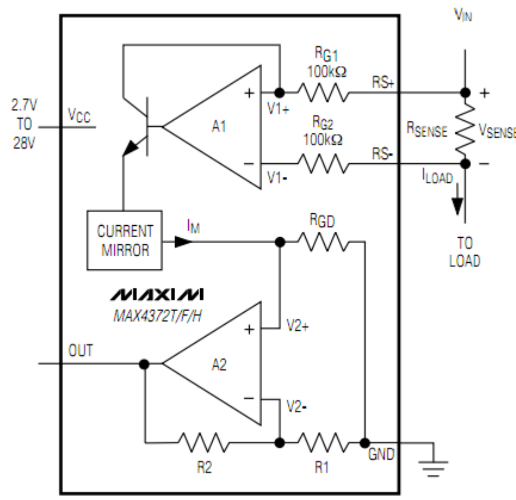
$V_{OC}=0.6*(1+R1/R2)$

V_{OC}: Output Voltage that causes C_{OUT} to go high

Figure 4.9: INA200 Circuit with Output Voltage and Overcurrent Equations

4.2.3 MAX4372H – Low Cost Micropower, High Side Current Sense Amplifier

The MAX4372H Micropower, Current Sense Amplifier is able to effectively track current the same way the MAX4373H is able to track current. Both ICs are identical in nature, but the MAX4372H does not have an integrated comparator, which means it is only able to track current rather than monitor for overcurrent conditions. In order to monitor for overcurrent, it would require an external comparator with a reference. While this does not have the exact functionality of the MAX4373H, it is cheaper and can be used to track the output current for the supplies that already have embedded overcurrent protection. Likewise, the MAX4372H is available in a very small, 6 pin SOT-23 package, which takes up a small amount of board space. Likewise, the MAX4372H is also available in a 20V/V gain package (MAX4372T) and a 50V/V gain package (MAX4372F). The circuit diagram for the MAX4372H is shown below in Figure 4.10.



$V_{OUT} = A_V*(R_{SENSE}*I_{LOAD})$, $A_V = 100V/V$

Figure 4.10: MAX4372H Circuit with Output Voltage Equation

V. TESTING

This section outlines the procedure and performance of each individual voltage supply and current tracking circuit. Prior to implementing the overall circuitry, each individual circuit was tested for functionality and performance. Depending on the performance of the chip, it was then implemented along-side its counterpart, combining current tracking, overcurrent protection and constant voltage supply. For the testing process, each power supply was built on a prototype board, measuring the output voltage at nominal input voltage across the load range of 2mA to 30mA load in 2mA increments, as well as at 25mA. For each current sense amplifier, the load was set to 4mA, 10mA, 20mA, 25mA and 30mA and the output was measured. The Kaveen USB Programming Box utilizes the following voltage rails: 5V Digital, 3.3V Digital, +15V, -15V and 24V. To aid in the testing process, a separate power supply test circuit was provided, containing each of the available power supply rails within the Kaveen USB Programming Box. Several designs were able to perform at specifications, but many designs were not able to meet the requirements as outlined within the project statement. The performance of each circuit is outlined below.

5.1 LT1121 – Micropower LDO Regulator Performance

The LT1121 was set up in the configuration shown in Schematic 1 on page 32 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the LT1121 is shown in Table 5.1 and Figure 5.1 below.

Table 5.1: LT1121 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	4.999
6	4.999
8	4.998
10	4.998
12	4.997
14	4.997
16	4.997
18	4.997
20	4.997
22	4.997
24	4.996
25	4.996
26	4.995
28	4.995
30	4.994

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(4.994-5.000)/5.000$

$\%LR = -0.12\%$

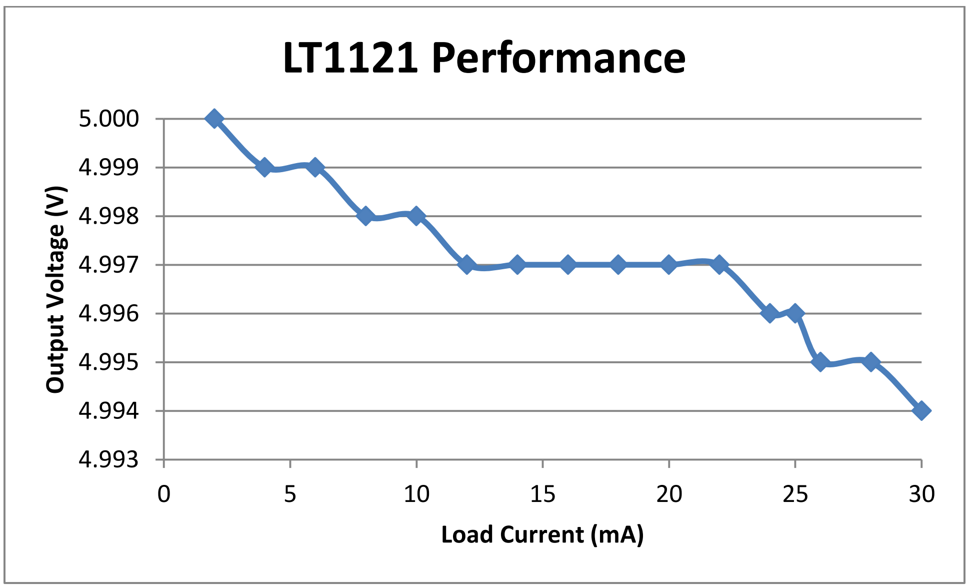


Figure 5.1: LT1121 Performance and Load Regulation

The LT1121 was an excellent candidate for the power supply. In regards to all the designs, the LT1121 was one of the simplest designs, utilizing a single resistive divider and an output capacitor. Along with its simplicity, it should be noted that due to its small amount of external components and simple 8-pin package, the LT1121's design implementation would take up a very small amount of board space. Unfortunately, one of the most important constraints on the voltage supply states that the output voltage (V_{Supply}) should not drop in excess of 1mV at a load of 25mA. As shown above, the output voltage of the supply dropped by approximately 5mV at 25mA. In this respect, the LT1121 has failed to meet the specifications outlined by the project requirements, so is not an eligible candidate for the power supply.

5.2 ICL7663S – Programmable Micropower LDO Regulator Performance

The ICL7663S was set up in the configuration shown in Schematic 2 on page 32 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the ICL7663S is shown in Table 5.2 and Figure 5.2 below.

Table 5.2: ICL7663S Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	4.997
6	4.995
8	4.993
10	4.990
12	4.987
14	4.995
16	4.998
18	4.999
20	4.992
22	4.899
24	4.788
25	4.578
26	4.278
28	3.829
30	2.758

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(2.758-5.000)/5.000$

$\%LR = -44.84\%$

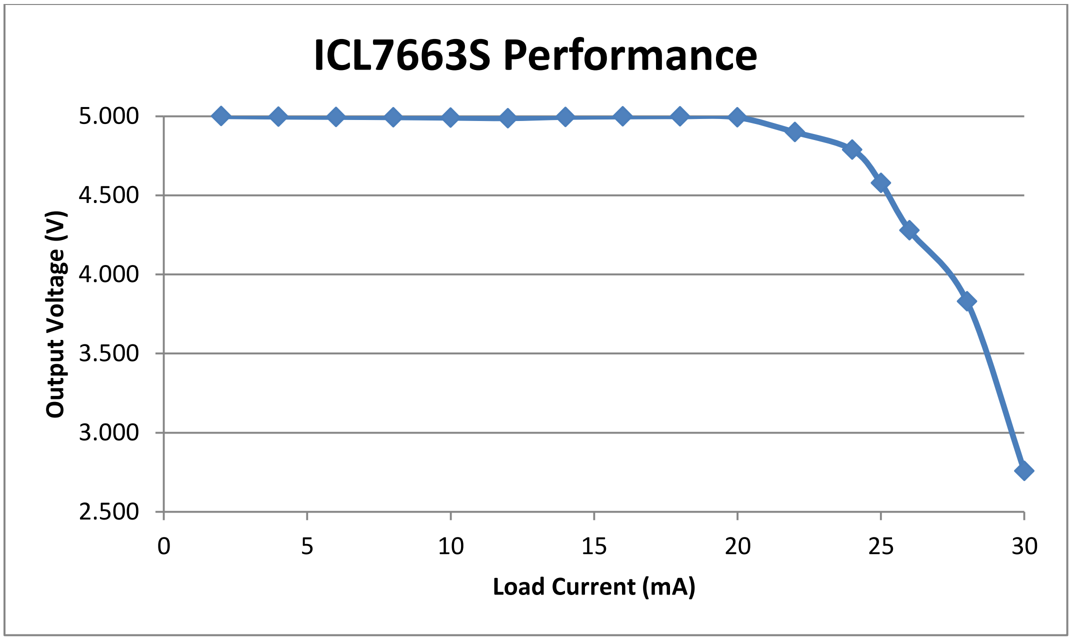


Figure 5.2: ICL7663S Performance and Load Regulation

The ICL7663S was an interesting and ambitious design candidate. While its design was slightly more complex, it was also able to achieve more than simple regulation. In addition to output voltage regulation, the ICL7663S implemented a 'set' current limit by using a known resistor value. As shown above, the performance of the ICL7663S was drastically out of specifications, dropping by approximately 400mV at 25mA load current, and eventually dropping by several volts at the full load value. It was found that, rather than employing a current limit that shuts down the supply when the current is above the overcurrent threshold, the ICL7663S employs "Foldback current limiting". With foldback current limiting, the ICL7663S reduces the output voltage and output current to below the current limit in order to ensure the output transistor is within its power dissipation limit. While the data sheet did not explicitly explain that it utilized this method, it would have been incredibly helpful to know, because foldback current limiting is exactly what the power supply should not employ, as it causes the supply to drop rather than turn off in the case of current exceeding the desired amount By looking at the data, it can also be seen that the voltage output is not linear in nature, which is also a large problem with the performance of this particular regulator.

5.3 LT1575 – Ultrafast LDO Regulator Performance

The LT1575 was set up in the configuration shown in Schematic 3 on page 33 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the LT1575 is shown in Table 5.3 and Figure 5.3 below.

Table 5.3: LT1575 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	5.000
6	5.000
8	5.000
10	5.000
12	5.000
14	5.000
16	5.000
18	5.000
20	5.000
22	5.000
24	5.000
25	5.000
26	5.000
28	5.000
30	5.000

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(5.000-5.000)/5.000$

$\%LR = 0\%$

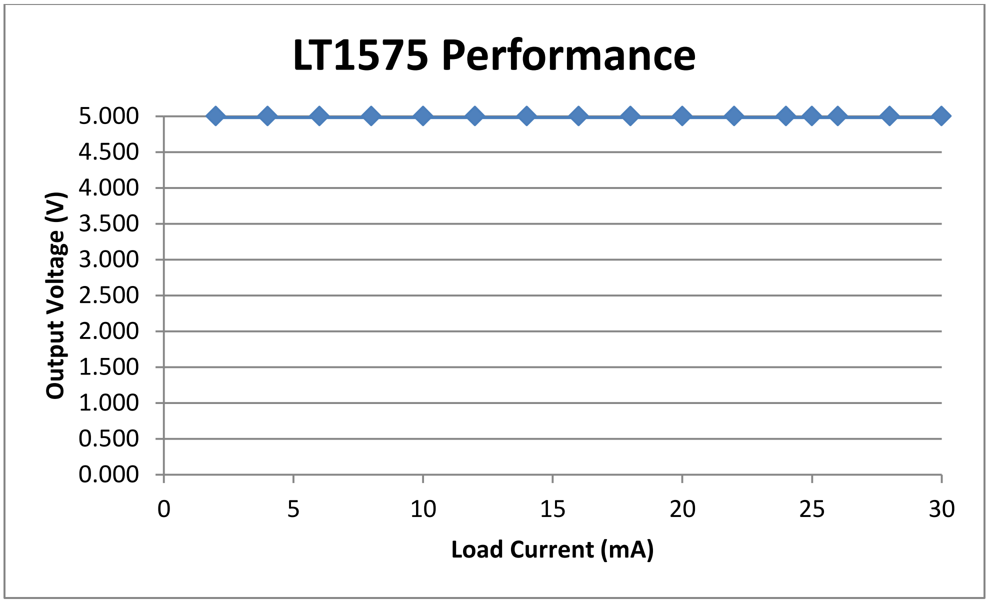


Figure 5.4: LT1575 Performance

The LT1575 was another design that implemented a current limit, determined by a specific chosen resistor value. Unfortunately, unlike many of the other designs, the LT1575 utilized several external components, calling for a capacitor bank consisting of up to 24 separate 1uF capacitors. In this regard, the LT1575 was largely overcomplicated, complex and would take up far too much board space to be considered a practical design. Aside from a large amount of board space, the performance of the LT1575 was flawless, having a load regulation of 0%. Likewise, the LT1575's built in current limit effectively turned the supply off when the load exceeded 30mA.

5.4 LM723 – High Precision Voltage Regulator Performance

The LM723 was set up in the configuration shown in Schematic 4 on page 34 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the LM723 is shown in Table 5.4 and Figure 5.4 below.

Table 5.4: LM723 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	5.000
6	5.000
8	5.000
10	5.001
12	5.001
14	5.001
16	5.002
18	5.002
20	5.002
22	5.002
24	5.000
25	4.996
26	4.985
28	4.895
30	4.543

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(4.543-5.000)/5.000$

$\%LR = -9.14\%$

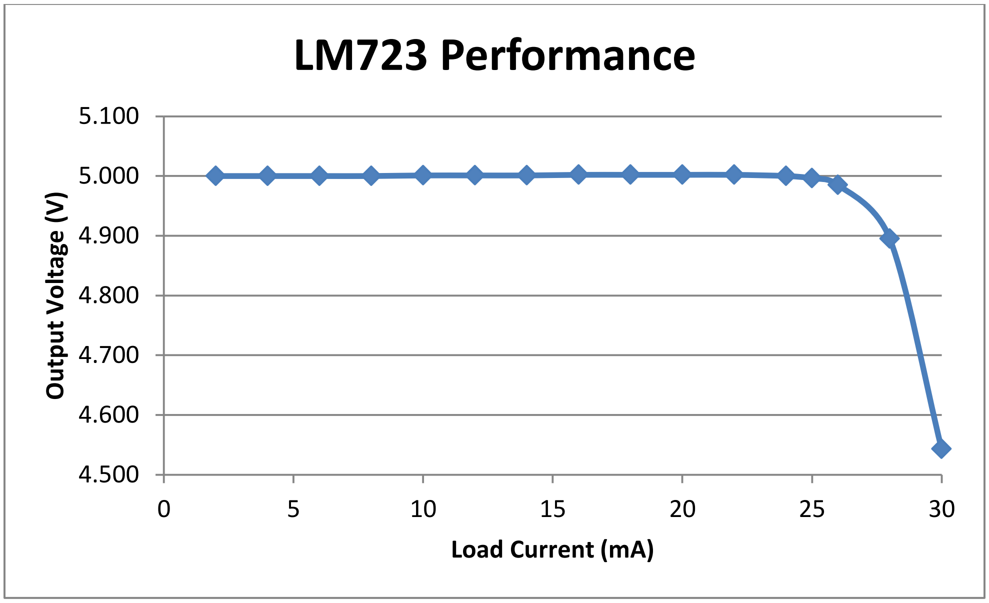


Figure 5.4: LM723 Performance

The LM723 was another simple regulator capable of many different applications, along with employing a current limit. Unfortunately, unlike each of the other designs, the LM723 does not have an embedded “shutdown” control. Instead, an external PNP Transistor would need to be utilized, causing the LM723 to take up more board space. Likewise, unlike the other designs, the LM723 is only available in a 14-pin package, which requires even more board space. Most importantly, as seen above, the supply voltage dropped by approximately 4mV at 25mA, falling out of the specifications of the project. Unfortunately, the LM723 is also ineligible for the power supply final design.

5.5 LP2951 – Micropower LDO Regulator Performance

The LP2951 was set up in the configuration shown in Schematic 5 on page 33 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the LP2951 is shown in Table 5.5 and Figure 5.5 below.

Table 5.5: LP2951 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT} (V)
2	5.000
4	5.000
6	5.000
8	5.000
10	5.000
12	5.000
14	5.000
16	5.000
18	5.000
20	5.000
22	5.000
24	5.000
25	5.000
26	5.000
28	5.000
30	5.000

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(5.000-5.000)/5.000$

$\%LR = 0\%$

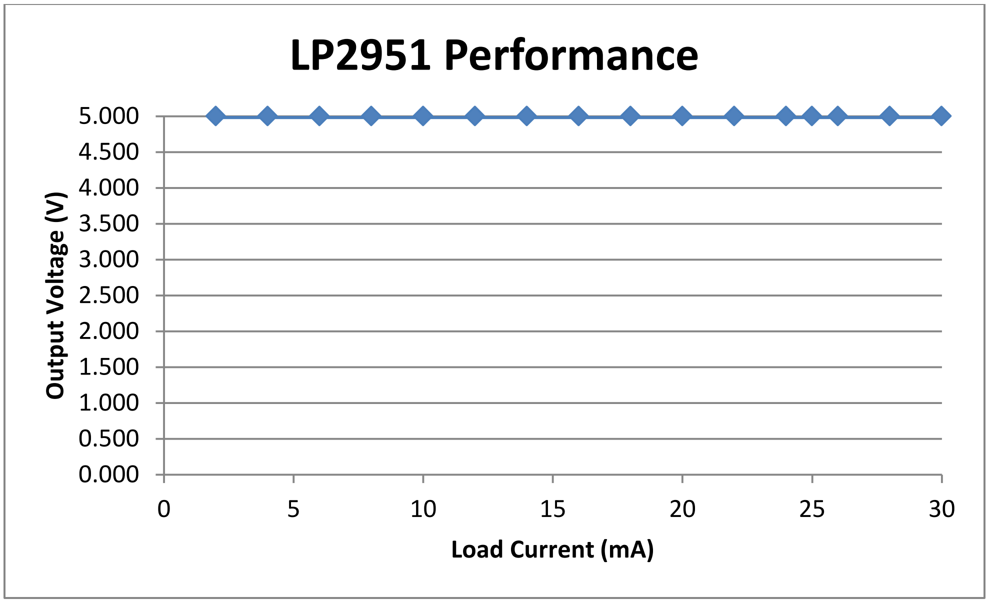


Figure 5.5: LP2951 Performance

Much like the LT1121, the LP2951 was a simple voltage regulator, requiring very few external components. In this regard, the LP2951 would take up a respectively smaller amount of board space when compared to other regulators. Unfortunately, the LP2951 does not have any embedded current limiting or overcurrent protection. As seen above, the output voltage of the supply does not vary across the entire 2mA to 30mA load range. With load regulation at 0%, the LP2951 is operating as an ideal regulator, where the full load and no load voltages are the same. While the performance of the LP2951 was exceptional, it should be noted that the voltage output drifted for the first 5 minutes while the components heated up. However, after the components were sufficiently heated, the regulator output did not drift or change as time or load changed.

5.6 LTC1771 – High Efficiency Step Down Converter Performance

The LTC1771 was set up in the configuration shown in Schematic 6 on page 34 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the LT1121 is shown in Table 5.6 and Figure 5.6 below.

Table 5.6: LTC1771 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	5.000
6	5.000
8	5.001
10	5.001
12	5.001
14	5.002
16	5.002
18	5.002
20	5.003
22	5.003
24	5.004
25	5.004
26	5.005
28	5.006
30	5.008

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(5.008-5.000)/5.000$

$\%LR = 0.16\%$

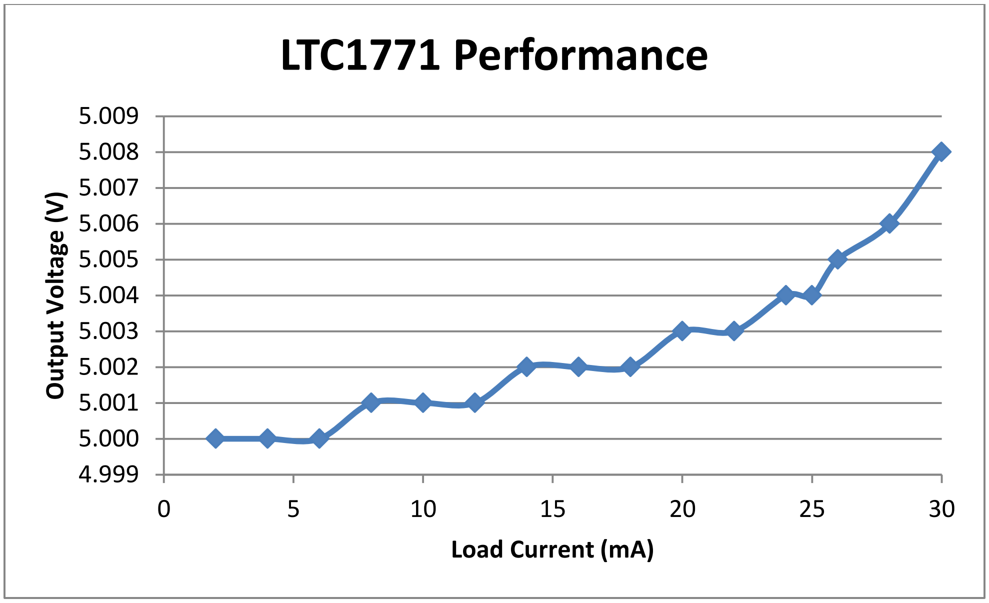


Figure 5.6: LTC1771 Performance

The LTC1771 requires several external components, including capacitors, inductors, a diode and an external transistor. Likewise, due to the nature of the LTC1771 switching regulator, the layout is subject to several design constraints. In addition, the LTC1771 requires very specific component choice in order to effectively and efficiently regulate to a designated 15V output. Unfortunately, the input of the LTC1771 is limited to 16V; while this will not be a problem for a 5V regulator, due to potential dropout associated with the device, the LTC1771 will likely require a separate 16V supply for 15V output operation. In regards to its performance, it can be seen that at lower loads (i.e., below 500mA output), the regulator does not act linearly. This is likely due to the fact that the converter is operating in discontinuous mode, where the current through the inductor falls to zero before the end of the switching period. Likewise, due to the nature of the LTC1771, the output also contains a notable voltage ripple. While this output ripple may be minimal (~45mV_{pp}), it can be considered undesirable. For these reasons, it can be seen that the LTC1771 is not eligible for the power supply circuit.

5.7 TL2575 – Simple Step Down Converter Performance

The TL2575 was set up in the configuration shown in Schematic 7 on page 34 in Appendix A. In this configuration, the load was varied from 2mA to 30mA and the output was measured at each point. The performance and load regulation for the TL2575 is shown in Table 5.7 and Figure 5.7 below.

Table 5.7: TL2575 Performance and Load Regulation

I_{LOAD}(mA)	V_{OUT}(V)
2	5.000
4	5.000
6	4.999
8	4.999
10	4.998
12	4.998
14	4.997
16	4.997
18	4.994
20	4.996
22	4.996
24	4.993
25	4.995
26	4.995
28	4.995
30	4.994

Percent Load Regulation:

$\%LR = 100\%*(V_{FullLoad}-V_{NoLoad})/V_{Nominal}$

$\%LR = 100\%*(4.994 -5.000)/5.000$

$\%LR = -0.12\%$

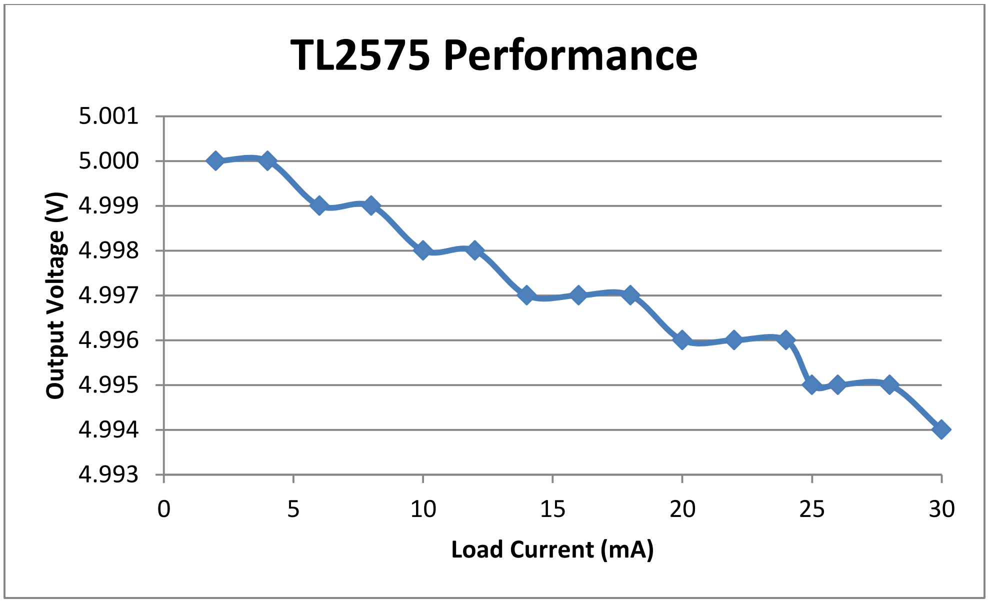


Figure 5.7: TL2575 Performance

Unlike the LTC1771, the TL2575 requires very few external components, requiring only an input capacitor, output capacitor, resistive divider and a Schottky diode. Likewise, the TL2575 is able to operate from a very wide input range, allowing the circuit to utilize the 24V rail within the Kaveen Programmer Box. Unfortunately, it can be seen from its performance, that it was not able to maintain its 5V regulation over 30mA. Likewise, due to the nature of the TL2575, the output also contains a notable voltage ripple. While this output ripple may be minimal (~20mV$_{pp}$), it can be considered undesirable. For these reasons, it can be seen that the LTC1771 is not eligible for the power supply circuit.

5.5 Current Sense Amplifier Performance

Each current sense amplifier was tested separately, as shown in Schematic 8 (MAX4373H) on page 35 in Appendix A, Schematic 9 (INA202) on page 35 in Appendix A and Schematic 10 (MAX4372H) on page 36 in Appendix A. Using the same value for a sense resistor (R_{SENSE} = 3Ω), the output voltages of the current tracking amplifier were measured at 4mA, 10mA. The performance of each current sense amplifier is shown in Table 5.8 and Figure 5.8 below.

Table 5.8: Current Sense Amplifier Performance

	MAX4373H	INA202	MAX4372H
I_{LOAD}(mA)	V_{OUT}(V)	V_{OUT} (V)	V_{OUT} (V)
4	1.1286	1.1964	1.08
10	2.8884	2.9723	2.8036
20	5.772	5.982	5.632
25	7.207	7.41	7.021
30	8.642	8.942	8.408

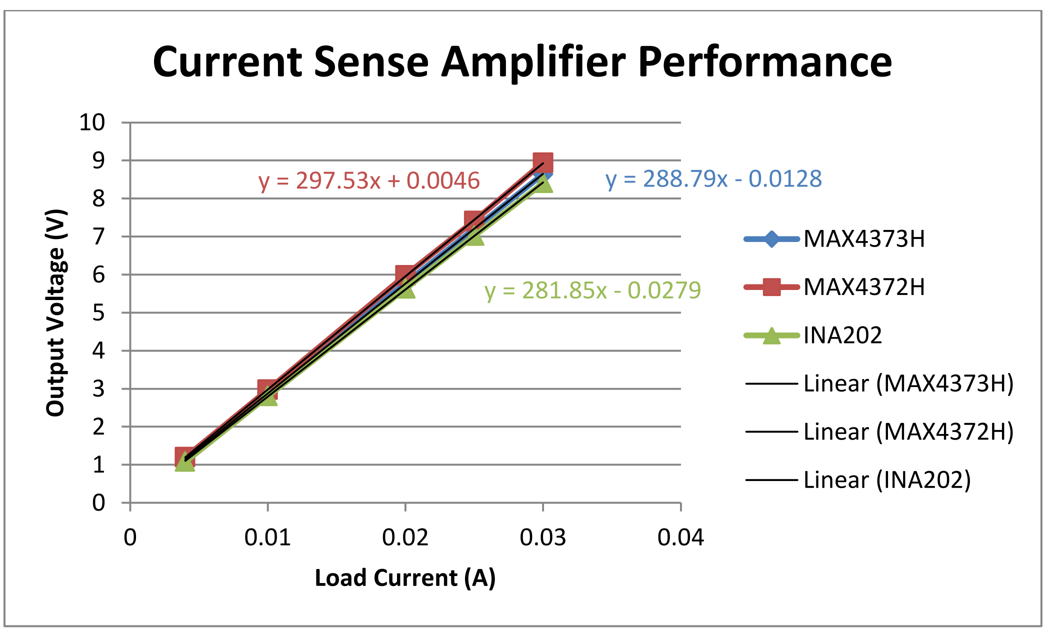


Figure 5.8: Current Sense Amplifier Performance

As noted above, the ideal Current Sense amplifier would have the formula of V_O=300*I_{LOAD}. From the performance curve shown above, it can be seen that the amplifier that performs closest to this formula is the MAX4373H, followed by the MAX4372H, and then followed by the INA202. While each of these amplifiers perform very closely, performance is of more importance than cost, so in the case where overcurrent must be sensed and shut of externally, MAX4373H should be implemented, otherwise MAX4372H should be implemented.

VI. CONCLUSIONS AND RECOMMENDATIONS

With the results obtained after testing and prototyping each design, several things were considered when making the final recommendation for the current tracking power supply. Overall, the most important part of the power supply was its ability to perform at spec, being less than 1mV drop at 25mA. Few circuits were able to meet this specification and were therefore discarded. Another important consideration was impact on the overall circuit within the Kaveen USB Calibration Box, namely noise affecting the surrounding circuitry. Several designs also implemented very complex circuitry or contained a large number of external components. With complexity comes issues with troubleshooting, isolating problems, and also board space. With this in mind, several options were discarded because they were overcomplicated and too large. Lastly, but also very important, is overall cost of the circuitry; many of the tested ICs hovered around the same cost, however a few were priced at much higher and some were priced much lower.

6.1 Problems Encountered and Troubleshooting

Originally, many of the regulators suffered from incredibly poor load regulation, dropping much more than 1mV at 25mA output. Before dismissing each regulator as underperforming, I was able to determine one of the causes of poor regulation. By adding a bypass capacitor between the output and feedback path of the regulator, the reference point is able to remain stable and allow for proper regulation across the feedback path. In other words, by adding the bypass capacitor, the output voltage will become more stable as the load current varies. The effect of the bypass capacitor was clearly seen in the case of the LP2951, where the output voltage tended to oscillate or remain unsteady at lower loads, causing the supply to drop by approximately 8mV when varying the load from 2mA to 30mA. By adding a small 0.01uF bypass capacitor, the regulator was able to operate with no voltage drop across the output at full load.

Another problem was noted in the performance of the current sense amplifier for current tracking. While the amplifiers were stated to have a set gain, each amplifier was subject to a particular gain error as well as an offset error, both of which would potentially cause a change in desired current tracking output. While the error associated may be small, it could lead to inconsistencies between each calibration box. In order to account for and correct the gain and offset errors, the amplifier would need to implement a gain adjustment as well as an offset adjustment. By utilizing a variable sense resistor, the gain could be adjusted to set the steepness of the “slope” for the current sense amplifier. In addition, by dropping the ground reference to an adjustable negative voltage, the offset can then be adjusted.

6.2 Final Circuit Recommendation

In the end, the design chosen implements the LP2951 as a constant voltage supply with a MAX4373H for current tracking and overcurrent protection. The design is shown in Schematic 11 in Appendix A on page 36. Of all the configurations, the overall component cost to implement the design was approximately $18US, coming to be one of the cheapest to implement of all design configurations. In this same respect, the size of the dual layer, surface mount PCB for the design was 4.6cm x 4.3cm (19.78cm^2), which is significantly smaller than Kavlico’s current implementation of 29cm^2. With this design, careful constraints are not needed for component placement and its output and overcurrent threshold are easily adjustable using potentiometers (P1 and P2 respectively). Likewise, with the added span and offset adjustments (P3 and P4 respectively), each circuit can be set to utilize the entire 0-10V range of an ADC or microcontroller. Lastly and most importantly, the LP2951 had flawless performance over the entire operating range of 2mA to 30mA, the only drawback being that the chip needs to heat up before reaching its maximum regulation. While this may seem like a significant drawback, the Kaveen USB Programmer Boxes are required to be turned on and left to heat for approximately 30 minutes before their initial calibration.

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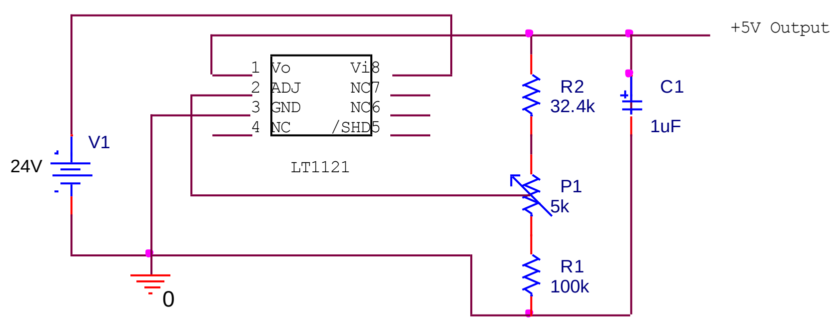
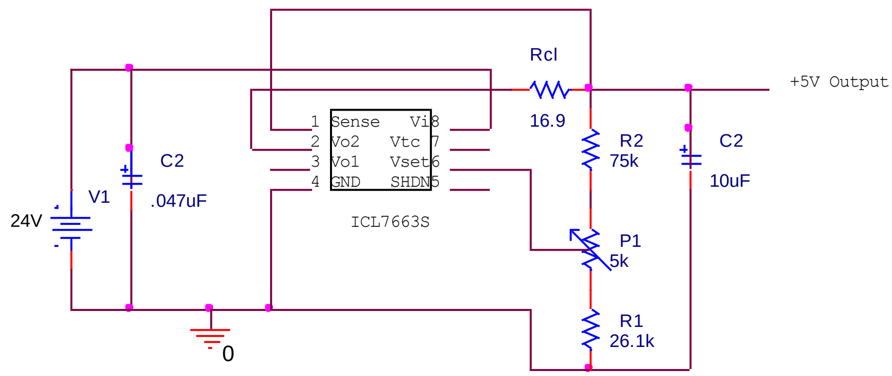
APPENDICES

A. Schematics

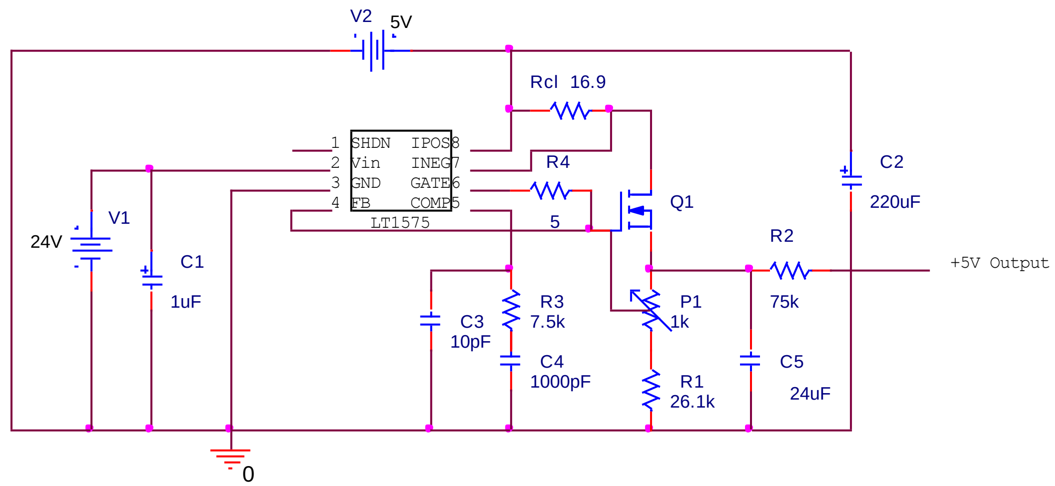
Schematic 1: LT1121 – Micropower Low Dropout Regulator with Shutdown



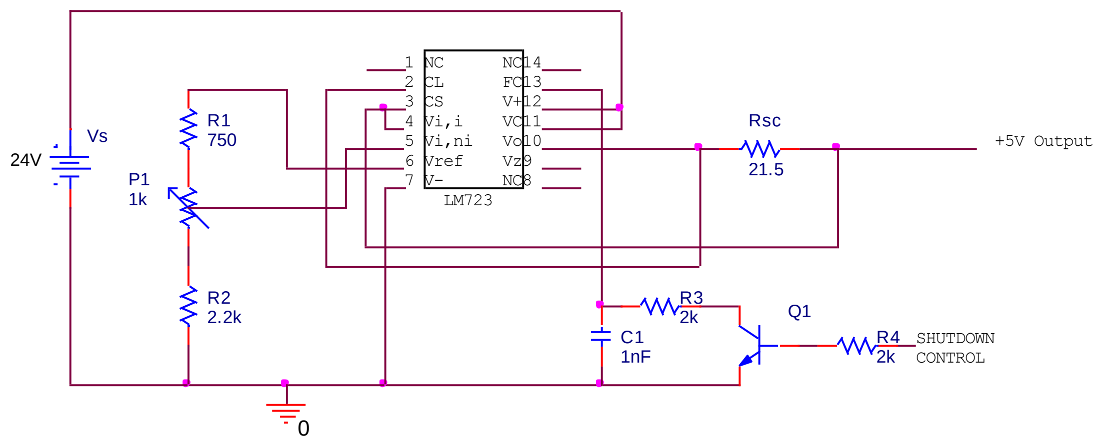
Schematic 2: ICL7663S – Programmable Micropower Voltage Regulator



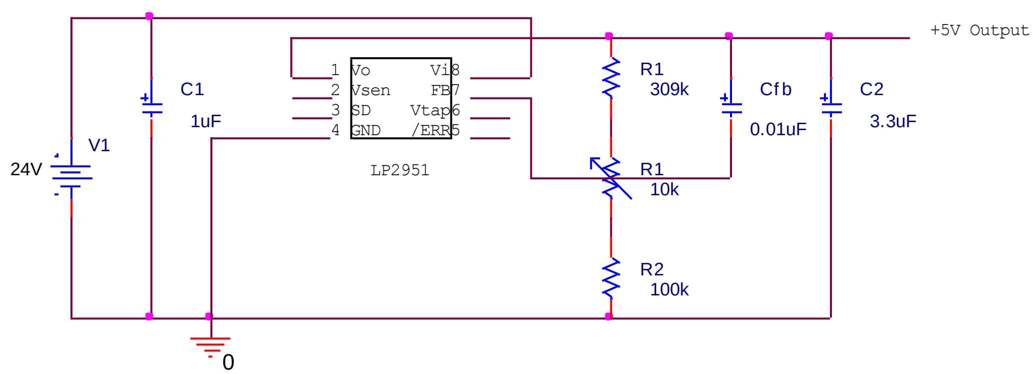
Schematic 3: LT1575 – Ultrafast Transient Response, Low Dropout Regulator



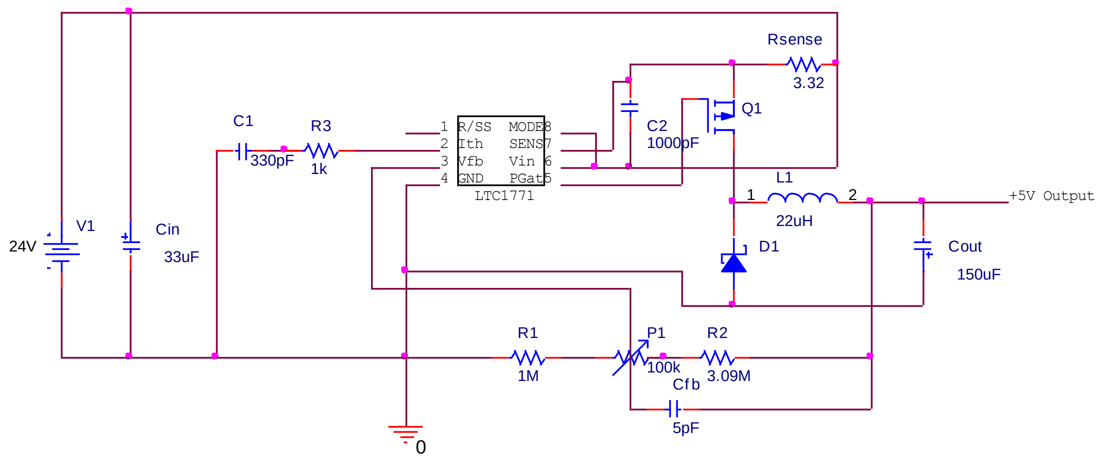
Schematic 4: LM723 – High Precision Voltage Regulator with Current Limit



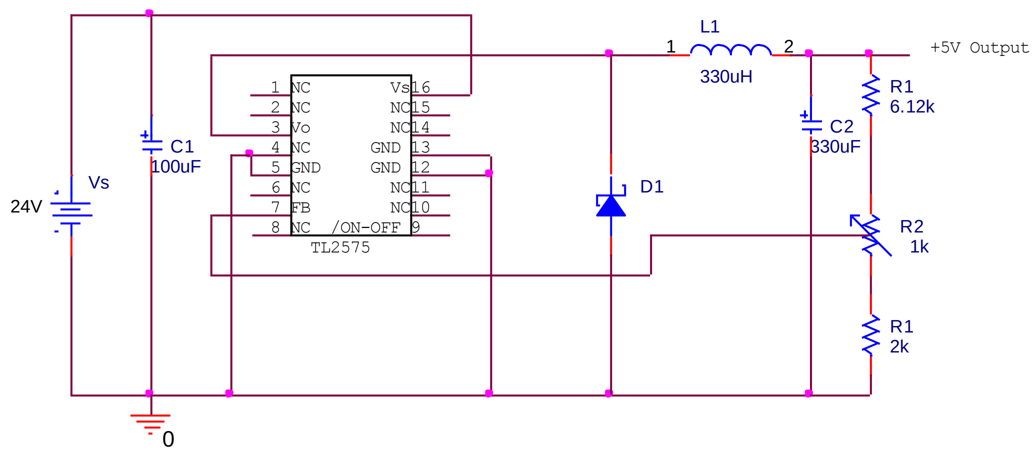
Schematic 5: LP2951 – Micropower Low Dropout Voltage Regulator with Shutdown



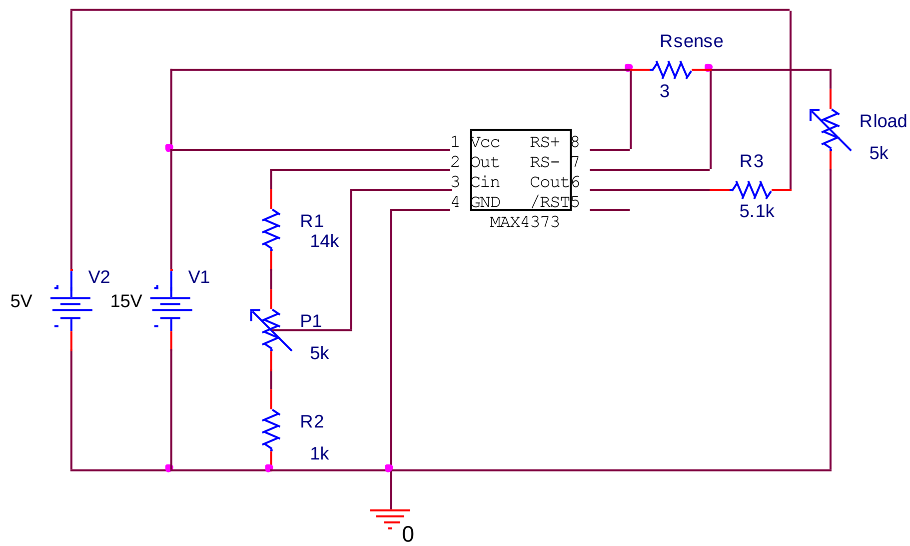
Schematic 6: LTC 1771 – High Efficiency, Step Down DC-DC Controller



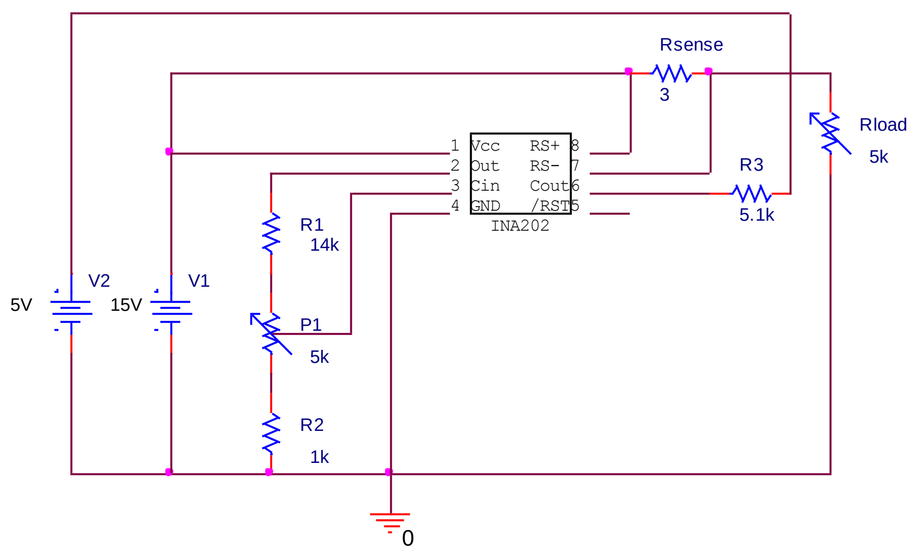
Schematic 7: TL2575 – Simple High Efficiency Step-Down Switching Voltage Regulator



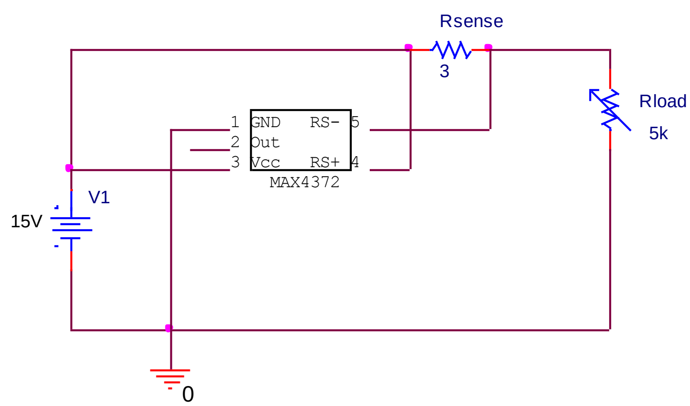
Schematic 8: MAX4373H – Micropower, High Side Current Sense Amplifier, Comparator and Reference



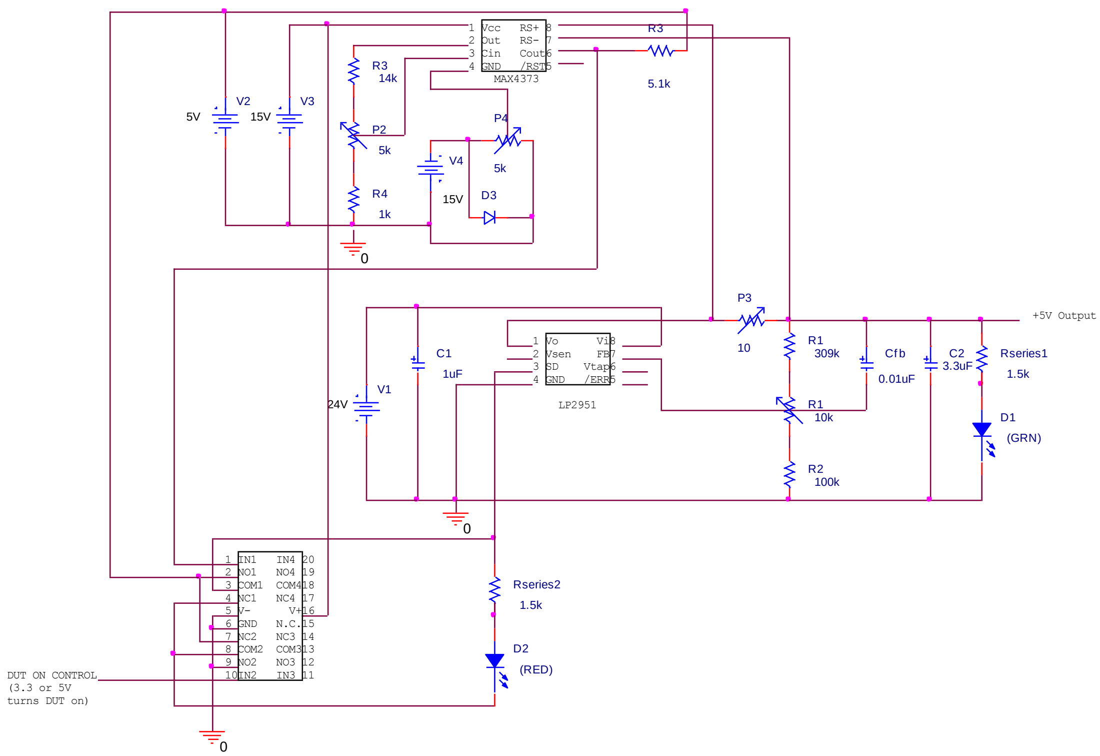
Schematic 9: INA202 – High Side Current-Shunt Monitor with Comparator and Reference



Schematic 10: MAX4372H – Low Cost Micropower, High Side Current Sense Amplifier



Schematic 11: Final Design Implementation with LP2951 and MAX4373H



B. Parts List and Cost of Design

LT1121 Overall Cost to Implement Design:

Part#	Value	Cost($)
LT1121		3.20
R1	100kΩ	0.04
P1	5kΩ	1.07
R2	32.4kΩ	0.04
C1	1uF	0.38
MAX333		9.61
MAX4373H		3.43
Rsense	3Ω	1.15
R4	14kΩ	0.04
P2	2kΩ	0.25
R5	1kΩ	0.04
R6	5.1kΩ	0.04
D1+D2		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $20.59

ICL7663S Overall Cost to Implement Design:

Part#	Value	Cost($)
ICL7663		3.42
R1	26.1kΩ	0.02
P1	5kΩ	0.25
R2	75kΩ	0.04
Rcl	16.9Ω	0.04
C1	.047uF	0.10
C2	10uF	0.20
MAX333		9.61
MAX4372T		1.97
D1+D2		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $16.95

LT1575 Overall Cost to Implement Design:

Part#	Value	Cost($)
LT1575		4.75
R3	7.5kΩ	0.04
R4	5Ω	0.25
Rcl	1.69Ω	0.08
R1	26.1kΩ	0.04
R2	75kΩ	0.04
P1	5kΩ	0.25
C1	1uF	0.22
C2	220uF	3.97
C3	10pF	0.07
C4	1000pF	0.06
C5	24uF	5.28
IRFZ24		1.41
MAX333		9.61
MAX4372H		1.97
D1+D2		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $29.34

LM723 Overall Cost to Implement Design:

Part#	Value	Cost($)
LM723		4.75
R1	750Ω	0.04
P1	1kΩ	0.25
R2	2.2kΩ	0.08
R3	2kΩ	0.04
R4	2kΩ	0.04
P1	1kΩ	0.25
C1	1uF	0.22
Rsc	21.6Ω	0.04
2N3646		1.54
MAX333		9.61
MAX4372T		1.61
D1+D2		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $19.77

LP2951 Overall Cost to Implement Design:

Part#	Value	Cost($)
LP2951		0.60
R1	309kΩ	0.02
P1	10kΩ	0.25
R2	100kΩ	0.04
Cfb	.01uF	0.56
C1	1uF	0.22
C2	3.3uF	0.14
MAX333		9.61
MAX4373H		3.43
P3	10Ω	0.61
R3	14kΩ	0.04
P2	2kΩ	0.25
R4	1kΩ	0.04
R5	5.1kΩ	0.04
D1+D1		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04
D3		0.42
P4	5kΩ	0.25

Total Cost: $17.82

LTC1771 Overall Cost to Implement Design:

Part#	Value	Cost($)
LTC1771		5.38
R1	1MΩ	0.04
R2	3.09MΩ	0.04
P1	100kΩ	0.25
Rsense	3.4Ω	0.08
R3	10kΩ	0.04
L1	33uH	1.28
Cout	150uF	1.51
Cin	44uF	0.80
Cfb	5pF	0.08
D1		0.42
C1	330pF	0.56
C2	1000pF	0.08
IRLML5103PBFCT		0.4
MAX333		9.61
MAX4372H		1.97
D2+D3		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $23.84

TL2575 Overall Cost to Implement Design:

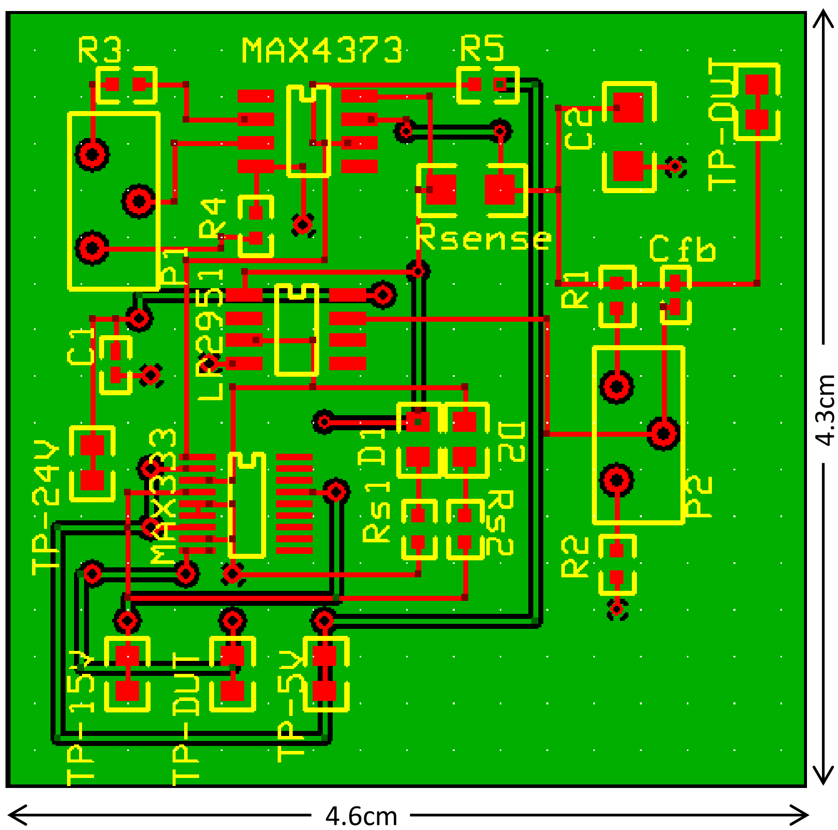
Part#	Value	Cost($)
LTC1771		5.38
R1	2kΩ	0.04
R2	6.12kΩ	0.04
P1	1kΩ	0.25
Rsense	3Ω	1.15
L1	330uH	1.73
Cout	330uF(e)	0.30
Cin	100uF(e)	0.80
Cfb	5pF	0.08
D1		0.42
IRLML5103PBFCT		0.4
MAX333		9.61
MAX4373H		3.43
D2+D3		1.22
Rseries1	1.5kΩ	0.04
Rseries2	1.5kΩ	0.04

Total Cost: $24.93

C. Printed Circuit Board Layout and Sizing

Final Design Implementation with LP2951, MAX333 and MAX4373

PCB Layout:



Total Area: 19.78cm^2