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***Design Report***
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# SIO2MKR USB Split Rail Power Supply

## Abstract

The SIO2MKR power supply regulates 5V USB power input into independently adjustable regulated split rail DC outputs. The design implements a tracking pre-regulator to maximise power output, while maintaining suitable ripple performance for low-speed analogue electronic loads. The design is intended for applications such as home analogue electronics with limited resources, low power demands, low user expertise, and low cost / high volume production.

This design was commissioned by the University of Cape Town and is made available publicly as Open Hardware under the CERN Open Hardware Licence v2 Permissive.

## Design Resources

| Resource | Location |
|---|---|
| Open Hardware Repository | GitHub |
| Datasheet | *Under Work* |
| PCB Project | Altium 365 |
| Schematic | Appendix A |
| Gerber Files | Altium 365 |
| Fabrication Drawing | Appendix B |
| Assembly Drawing | Appendix C |
| Bill of Materials | Appendix D |

## Features

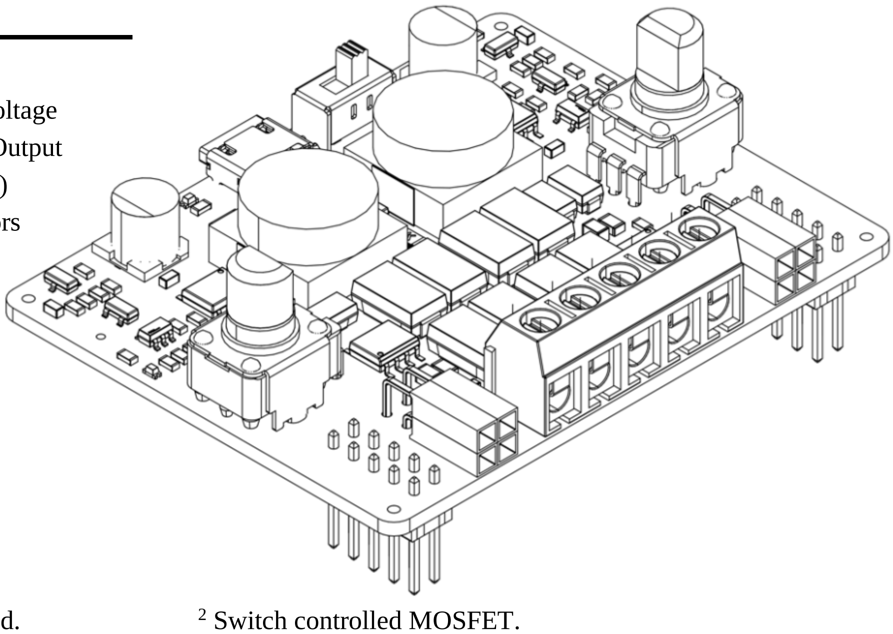
- 5V USB Power Input
- Independently Adjustable Output Voltage
- ±1.25 to ±10.5V at 40mA (0.84W) Output
- Tracking Pre-Regulation (MC34063)
- LM317 and LM337 Linear Regulators
- 3 stage protection (2x ICs, 1x Fuse)[1]
- Power Switch[2]

## Applications

- General Purpose Electronics Prototyping
- School and University Programmes
- Hobby Electronics
- Electronics Development Programmes

## Additional Resources

| Resource | Location |
|---|---|
| MC34063 Datasheet | ON Semiconductor |
| LM317 Datasheet | ON Semiconductor |
| LM337 Datasheet | Texas instruments |
| PCB Specifications | JLCPCB |
| Voltage Divider Script | Appendix E |
| CERN OHL v2 P | CERN, Appendix F |



[1] High Power 5V Output is only fuse protected.

[2] Switch controlled MOSFET.

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# 1 System Description

This design implements a parallel boosting and inverting switching regulator, both utilising the MC34063 — a ubiquitous, low cost and robust power converter. Each switched output is then passed through the LM317 (positive) and LM337 (negative) adjustable linear regulators to eliminate switching noise. The regulators are adjusted using two potentiometers, compensated for linearity over the range of operation. A feedback network implements 3V tracking pre-regulation between the switched and linearly regulated outputs, similar to many “hybrid” DC bench power supplies. In conjunction with a generous 400µF tantalum capacitor bank (per rail); this configuration results in an output voltage ripple suitable for most low-speed analogue electronics projects and experiments.

# 2 Design Specifications

| Symbol | Name | Value | | |
|---|---|---|---|---|
| | | **Minimum** | **Typical** | **Maximum** |
| $V_I$ | DC Input Voltage | 4.6V | 5.0V | 5.5V |
| $P_I$ | Input Power | 5W | | |
| $V_O$ | Output Voltage Range (Each Rail) | ±1.2V | | ±10V5 |
| $I_O$ | Rated Output Current (Rail to Rail) | | | 40mA |
| $I_{O\_PP}$ | Rated Output Current (Positive Rail to Ground) | | | 60mA |
| $I_{O\_PP}$ | Rated Output Current (Ground to Negative Rail) | | | 40mA |
| $V_R$ | Ripple Voltage (Switching Regulator) | | | 50mVpp |
| $V_{TRACK}$ | Pre-regulator Tracking Voltage | | 3.0V | |
| $V_{SR\_PP}$ | Boosting Regulator Output Range | $V_I$ | | 13V75 |
| $V_{SR\_NN}$ | Inverting Regulator Output Range | 0V | | -13V75 |
| $f_{SR}$ | Switching Frequency | 24kHz | 33kHz | 42kHz |
| $I_{L\_pk}$ | Peak Switching Current (Per Regulator) | | 0A44 | |
| $V_{LED\_ON}$ | LED Indicator ON Threshold | | ±5V | |
| $V_{LED\_OFF}$ | LED Indicator OFF Threshold | | ±1V5 | |
| $I_{FUSE\_USB}$ | Input Non-resettable Fuse Rated Current | | 3A | |
| $I_{FUSE\_PTC}$ | Output PTC Fuse Rated Current | | 460mA | |

# 3 Functional Diagram

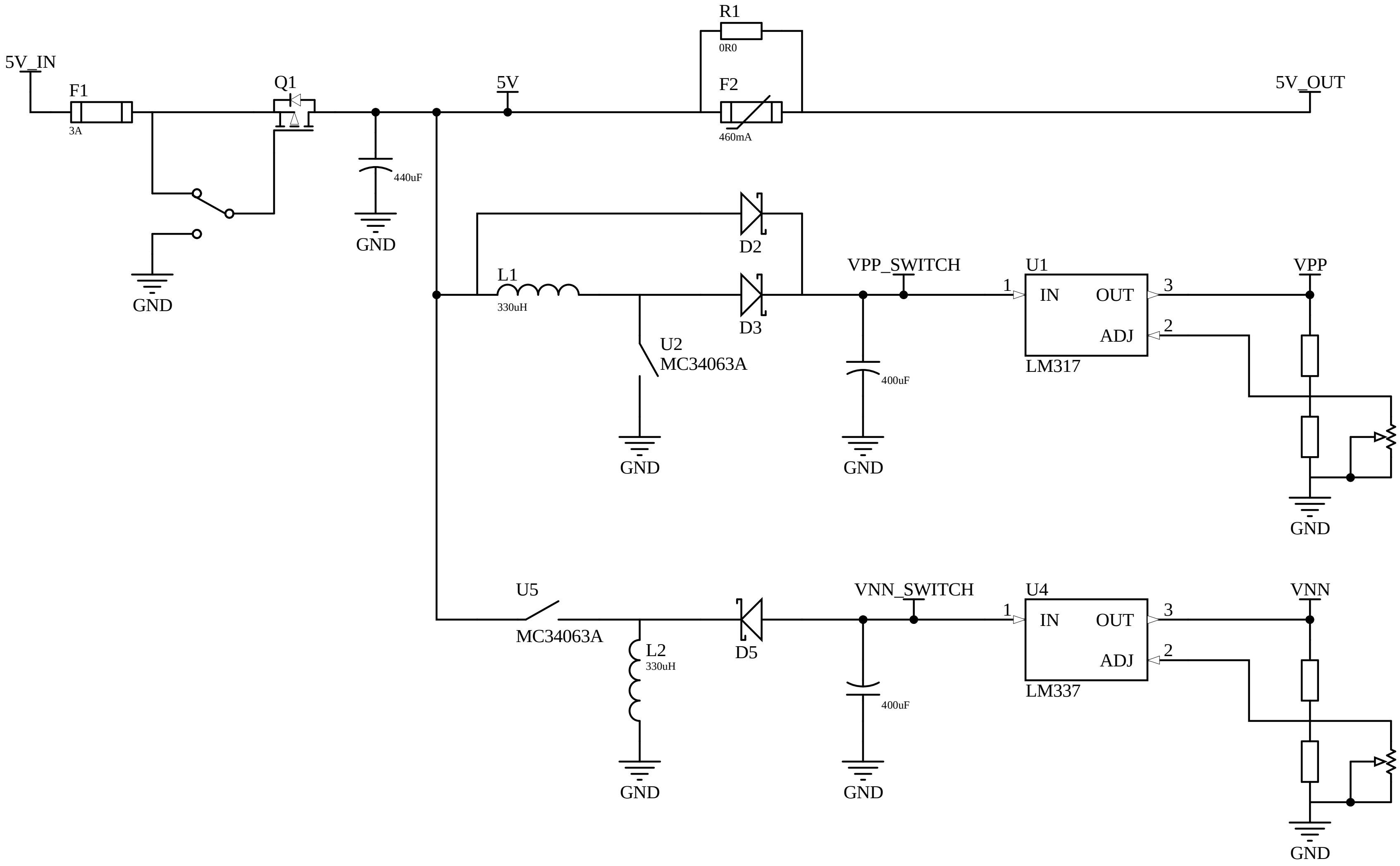



**FIGURE 1: FUNCTIONAL DIAGRAM**

# 4 Component Selection Criteria

The selection process for each component is not detailed, however in general the following criteria were applied in decreasing order of priority:

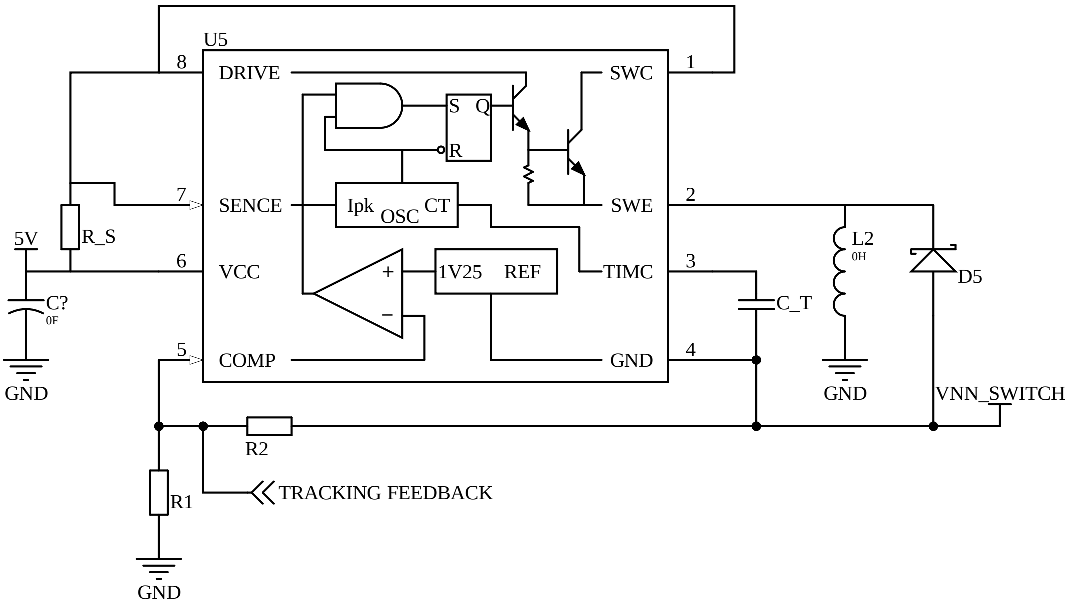
1. Any directly-applicable, fixed specifications.
2. Available via JLCPCB SMT Assembly (limited subrange LCSC.com)
3. Active Part, Stock & Availability (150 Units Minimum at time of selection)[3]
4. Basic Part (JLCPCB SMT Assembly designation)
5. Performance & Features
6. Component Package
7. Cost (100 to 1000 units)
8. Component-specific comparisons, RoHS, manufacturer & other terminal criteria.

[3] Due to the 2021 global chip shortage, this criterion was significantly increased in priority than normal.

# 5 Design Calculations

Where an equation or symbol is quoted without reference to the visible circuitry, the source is to be assumed to be the datasheet of the relevant component.

## 5.1 Inverting Regulator




**CIRCUIT 1: INVERTING REGULATOR**

### 5.1.1 Feedback Voltage Divider

Note: this voltage divider effectively limits the maximum output, given no feedback from the tracking feedback path. Additionally, the common node of the MC34063 is referenced to the negative output rail. The 1V25 reference voltage is therefore situated as 1V25 above $V_{NN}$, NOT 1V25 below GND.

Let $V_{O\_MAX}$ = -14V

$$V_O = V_{FB}\frac{R_1 + R_2}{R_1}$$

- $V_{FB}$ = -1V25

From the above, the script in Appendix E resolved the following values:

- $R_1$ = 5K6
- $R_2$ = 56K

Rated $V_{O\_MAX}$ = -13V75.

### 5.1.2 Switching Times

$$T = t_{on} + t_{off} = \frac{1}{f}, \qquad \frac{t_{on}}{t_{off}} = \frac{|V_O| + V_F}{V_{in} - V_{sat}}, \qquad t_{on} = \frac{T}{1 + \frac{1}{t_{on}/t_{off}}}$$

- $V_O$ = 13V75
- $V_{F\_MAX}$ = 0V55 (SS34 SBR)
- $V_{sat}$ = (1V0 ; 1V3) — Darlington
- $V_{in}$ = (4V6 ; 5V25) — USB Specification
- f = (24 ; 42) kHz — Typical Range

Due to the switch being above the inductor, a Darlington configuration was necessary.

Therefore:

- $T_{MAX}$ = 41.7µs  $T_{MIN}$ = 23.8µs
- $(t_{on}/t_{off})_{MAX}$ = 4.33
- $(t_{on}/t_{off})_{MIN}$ = 3.24
- $t_{ON\_MAX}$ = 33.9µs
- $t_{ON\_MIN}$ = 18.2µs

### 5.1.3 Overcurrent Protection

$$I_{L_{pk}} = \frac{V_{th}}{R_s}$$

- $V_{th}$ = 0V3

The inductor will be selected with overspecification on current handling to improve conduction losses. Therefore, the inductor rated current is not a consideration here.

The power supply is rated as a minimum of $5W = 5V \times 1A$. Neglecting all small loads, and assuming the worst-case scenario of both the inverter and booster switching on simultaneously at peak current, each regulator is permitted 1A/2 = 0.5A peak current. Therefore, set 0.5A as the current limit.

Given a more powerful input, this current limit can be increased by modifying $R_S$ within the rated limits of the inductor and MC34063, which will increase the output current capability.

$$\therefore R_s = \frac{0V3}{0A5} = 0R6 \approx 0R68$$

$$I_{L_{pk}} = \frac{0V3}{0R68} = 0A44$$

### 5.1.4 Output Current

$$I_{O_{MAX}} = \frac{I_{pk}}{2\left(\left(\frac{t_{on}}{t_{off}}\right)_{MAX} + 1\right)} = \frac{0A44}{2(4.33 + 1)} = 41mA$$

Therefore rate $I_{O_{RATED}} = 40mA$

## 5.1.5 Inductor Value

$$L_{MIN} = \frac{V_{in_{MIN}} - V_{sat_{MIN}}}{I_{L_{pk}}} t_{on_{MAX}} = \frac{4V6 - 1V0}{0A44} 33.9\mu s = 277\mu H \approx 330\mu H$$

Note: Inductance value options are fairly limited on JLC.

Select: **SWRB1207S-33MT**

- L = 330μH
- $I_R$ = 0A95

Current handling capability was over specified to reduce inductor resistance, within a reasonable footprint size. Height was unlimited.

## 5.1.6 Output Capacitance

$$C_O = \frac{9 I_{O_{MAX}} t_{on_{MAX}}}{V_{ripple_{pp}}}$$

Specify $V_{ripple} = 50mVpp$

$$\therefore C_{O_{MIN}} = \frac{9 \times 46.6mA \times 32.9\mu s}{50mV} = 276\mu F \approx 3 \times 100\mu F$$

1 additional capacitor was later added given available board area.

Select: **293D107X9016D2TE3**

- Tantalum Electrolytic
- 100μF
- 16V

Tantalum capacitors were selected for their superior performance at higher voltage operation than MLCCs (DC bias effect), the fixed polarity of the rails, the required capacitance, and the available board area. 16V was sufficient assuming nominal operation of the MC36063 feedback divider with 2V headroom for overshoot.

## 5.1.7 Timing Capacitor

$$C_T = 4.0 \times 10^{-5} Fs^{-1} \times t_{on_{MAX}} = 4.0 \times 10^{-5} Fs^{-1} \times 32.9\mu s = 1.32nF \approx 1nF$$

Rate at 16V (same as output capacitor).

This is not a critical component in value.

## 5.1.8 Input Capacitor

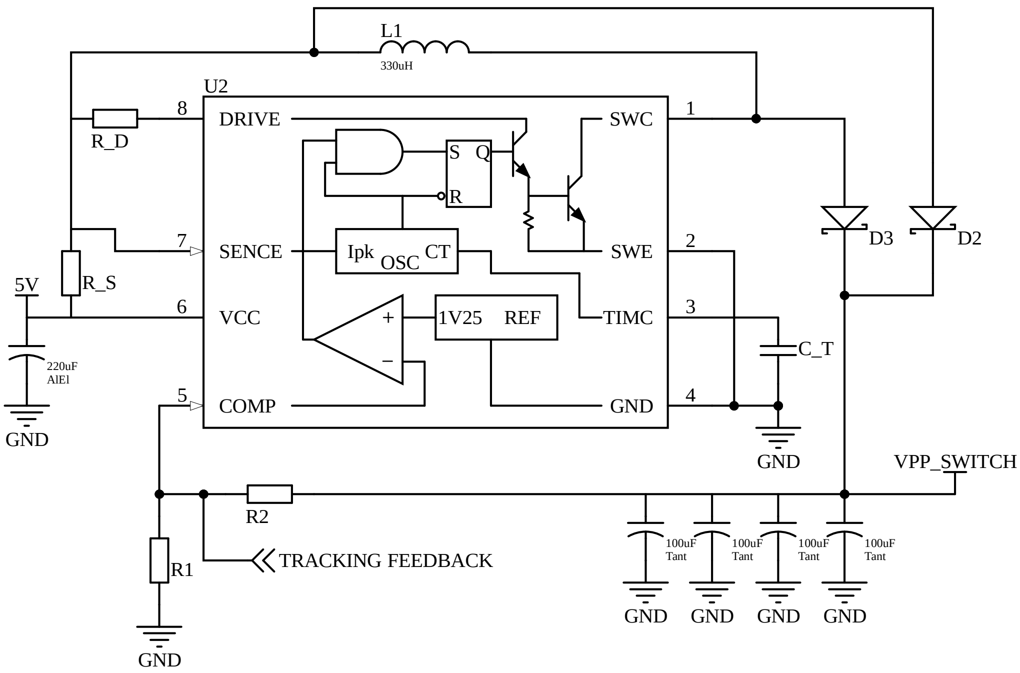
Assign 2x220μF AlEl Capacitors at 10V.

This is not a critical value in capacitance.

Although placing this component after the current sensing resistor may improve the maximum power capability of the device, this may result in triggering an overcurrent event on startup. Therefore, place these capacitors before the current sense resistor.

## 5.2 Boosting Regulator

Much of this design is identical to the inverting regulator. For brevity, where the same design equation applied to both the inverting and boosting regulator, the result achieved in the inverter is simply replicated upon the booster.




**CIRCUIT 2: BOOSTING REGULATOR**

### 5.2.1 Feedback Voltage Divider

This circuit matches exactly the same feedback reference voltage to the same (inverted) maximum output. However, the reference is 1V25 above ground, not 1V25 below the output rail. Therefore, the values are swapped in position.

- $R_1$ = 56K
- $R_2$ = 5K6

### 5.2.2 Switching Times

$$T = t_{ON} + t_{OFF} = \frac{1}{f}, \frac{t_{on}}{t_{off}} = \frac{V_O + V_F - V_{IN_{MIN}}}{V_{IN_{MIN}} - V_{sat_{MAX}}}, t_{on} = \frac{T}{1 + \frac{1}{t_{on}/t_{off}}}$$

- $V_O$ = 13V75
- $V_F$ = 0V55 (SS34)
- $V_{sat}$ = (0V45; 0V7) (Non-Darlington Configuration)
- f = (24; 42)kHz

$$\frac{t_{on}}{t_{off}} = \frac{13V75 + 0V55 - 4V6}{4V6 - 0V7} = 2.48$$

$$t_{on_{MAX}} = \frac{T_{MAX}}{1 + \frac{1}{\left(\frac{t_{ON}}{t_{OFF}}\right)}} = \frac{1}{24kHz\left(1 + \frac{1}{2.48}\right)} = 29.7\mu s$$

$$t_{on_{MIN}} = \frac{T_{MIN}}{1 + \frac{1}{\left(\frac{t_{ON}}{t_{OFF}}\right)}} = \frac{1}{24kHz\left(1 + \frac{1}{2.48}\right)} = 17.0\mu s$$

## 5.2.3 Overcurrent Protection

Same as Inverter:

- $R_S$ = 0R68
- $I_{pk}$ = 0A44

## 5.2.4 Output Current

$I_{O_{MAX}} = \frac{I_{pk}}{2\left(\frac{t_{ON}}{t_{OFF}}+1\right)} = \frac{0A44}{2(2.48+1)}$ =63mA

Since it is plausible that current sourced from $V_{PP}$ will also need to be sunk by $V_{NN}$, rate both supplies at the more constrained rating of $V_{NN}$, 40mA. However, for single supply operation, rate:

$I_{O_{PP_{RATED}}} = 60mA$

## 5.2.5 Inductor Value

$$L_{MIN} = \frac{V_{IN_{MIN}} - V_{sat_{MIN}}}{I_{pk}} t_{ON_{MAX}} = \frac{4V6 - 0V4}{0A44} 29.7\mu s = 283\mu H < 330\mu H$$

Therefore, in the interest of parts management, select the same inductor as the inverter.

## 5.2.6 Output Capacitance

These characteristics are identical to that of the inductor, and therefore the same bank of 4x100μF capacitors were used, spare for changing the polarity of the connection.

## 5.2.7 Timing Capacitor

$C_T$ = 1nF (Same as inverter)

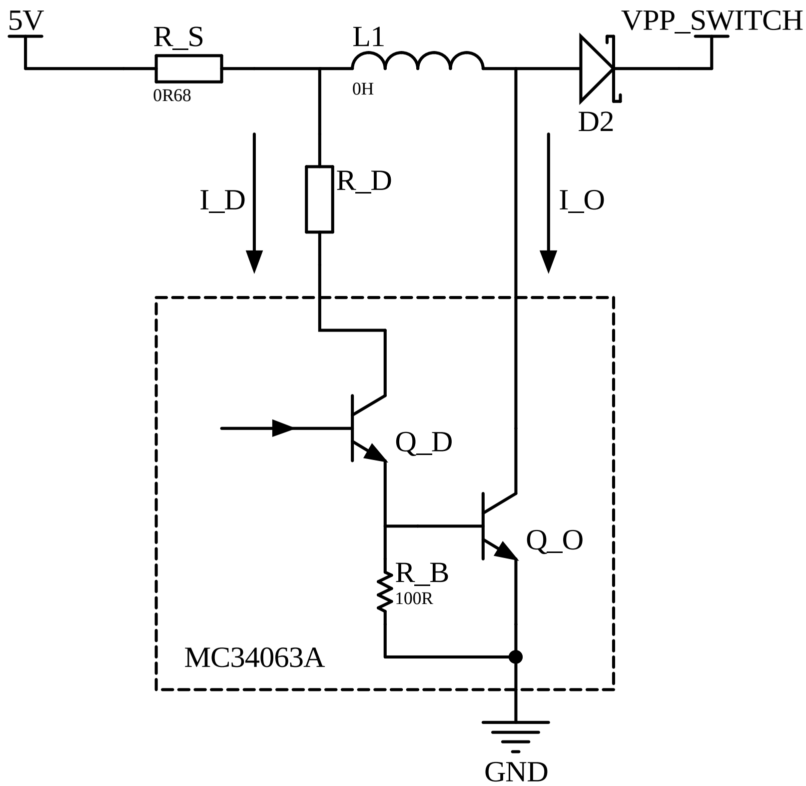
### 5.2.8 Forced Gain

It is recommended that:

$$\frac{I_{C_{OTP}}}{I_{C_{DRIVER}} - 7mA} \geq 10$$

This is interpreted as the power transistor within the Darlington transistor should not be forced to a gain less than 10. This specifically refers to the turn-off transition, where excessive overdrive will delay turn-off, thereby increasing the $t_{OFF}$ time with an initial low collector current (<300mA), which is problematic at higher switching frequencies (>30kHz).

From the circuit diagram the following derivation follows:




**CIRCUIT 3: DARLINGTON FORCED GAIN CIRCUIT**

$$I_{C_D} = \frac{V_{CC} - V_S - V_{CE_{O_{sat}}} - V_{BE_O}}{R_D} = \frac{V_{CC} - \left(I_{C_O} + I_{C_D}\right)R_S - V_{CE_{O_{sat}}} - 7mA \times R_B}{R_D}$$

$$\left(I_{C_O} + I_{C_D}\right)R_S + R_D I_{C_D} + R_B 7mA = V_{CC} - V_{CE_{O_{sat}}}$$

$$I_{C_O}R_S + I_{C_D}(R_D + R_S) + 7mAR_B = V_{CC} - V_{CE_{O_{sat}}}$$

$$I_{C_O}R_S + \left(I_{C_D} - 7mA\right)(R_D + R_S) + 7mA(R_D + R_S) + 7mAR_B = V_{CC} - V_{CE_{O_{sat}}}$$

$$I_{C_O}R_S + \left(I_{C_D} - 7mA\right)(R_D + R_S) + 7mA(R_B + R_D + R_S) = V_{CC} - V_{CE_{O_{sat}}}$$

By rearrangement, the gain condition is revealed, and the limitation applied:

$$\frac{I_{C_O}}{I_{C_D} - 7mA} = \frac{1}{R_S}\left(\frac{V_{CC} - V_{CE_{O_{sat}}}}{I_{C_D} - 7mA} - (R_D + R_S) - \frac{7mA}{I_O}(R_B + R_D + R_S)\right) \geq 10$$

In the gain condition, the approximation $I_{E_D} = I_{C_D} + I_{B_D} \approx I_{C_D}$is implicit.

Therefore $\frac{I_{C_O}}{I_{C_D}-7mA} = H_{FE}$:

$$\frac{1}{R_S}\left(\frac{V_{CC}-V_{CE_{O_{sat}}}}{I_{C_D}-7mA}-(R_D+R_S)-\frac{7mA}{I_{C_O}}(R_B+R_D+R_S)\right)=H_{FE}$$

By rearrangement:

$$\boldsymbol{R_D = \frac{\left(V_{CC}-V_{CE_{O_{sat}}}\right)H_{FE}-I_O R_S(H_{FE}+1)-7mA\cdot H_{FE}(R_B+R_S)}{I_{C_O}+7mA\cdot H_{FE}}}$$

The transistor saturation effects are most relevant at higher output collector currents (300mA), since this corresponds to a more active condition (as opposed to an inactive, non-conducting condition). Additionally, the saturation voltage of the drive transistor is unspecified, but is significant in the above result relative to $V_{CC}$ (5V) and is therefore approximated to be equal to the power transistor forced gain saturation voltage (0.45V). In summary:

- $V_{CC}$ = 5V
- $V_{CE\_D(sat)}$ = 0.45V
- $I_{C\_O}$ = 0.300A
- 

Given these conditions, with all other values specified, by computing the required drive resistor for a range of possible DC current gains, along with the corresponding drive current, the following figure is produced:

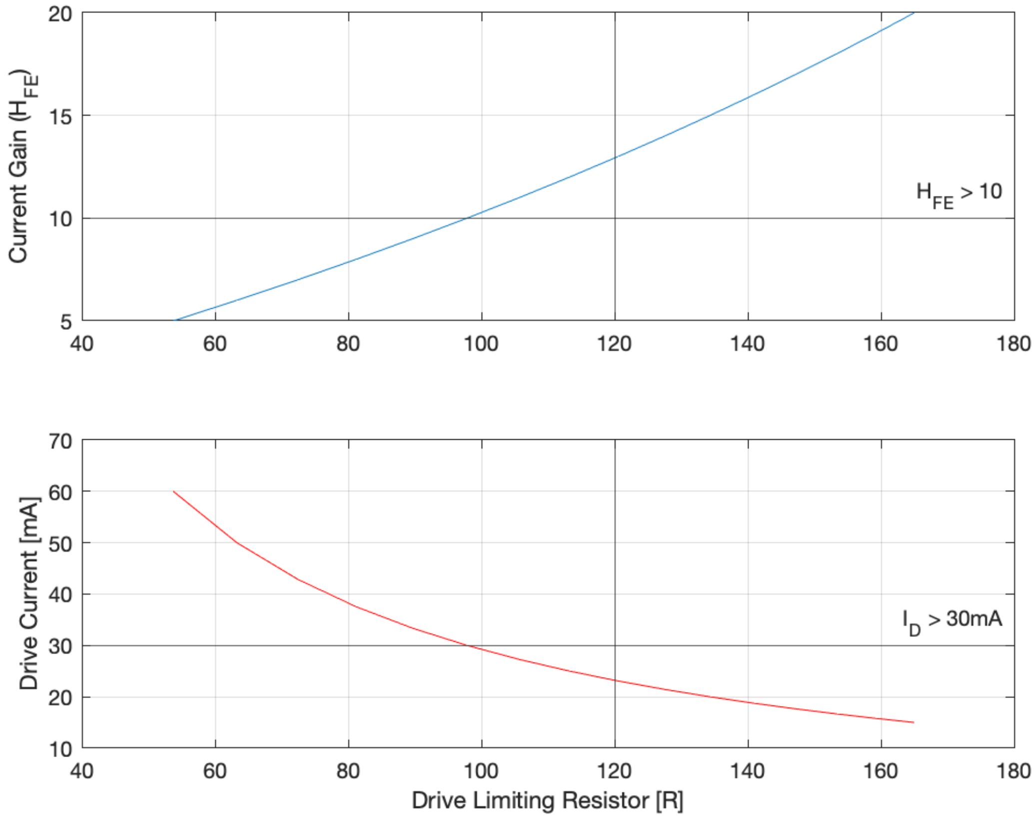



**FIGURE 2: FORCED GAIN CONDITIONS**

From this, it is observed that:

- The Drive Current is an approximately inversely proportional function of the Drive Limiting Resistance.

- Due to the fixed output current condition, the Darlington DC current is inversely proportional to the Drive Current, the therefore approximately directly proportional to the Drive Limiting Resistance.

This reaffirms the intuitive function of the drive current limiting resistor and shows that the effects of the current sense resistor are limited.

***Although the drive input could be connected directly to the 5V source, this tampers with the current limiting function of the MC34063 as 23mA is significant.***

It is therefore observed that the minimum E12 resistor value that satisfies the recommended conditions is **120R.**

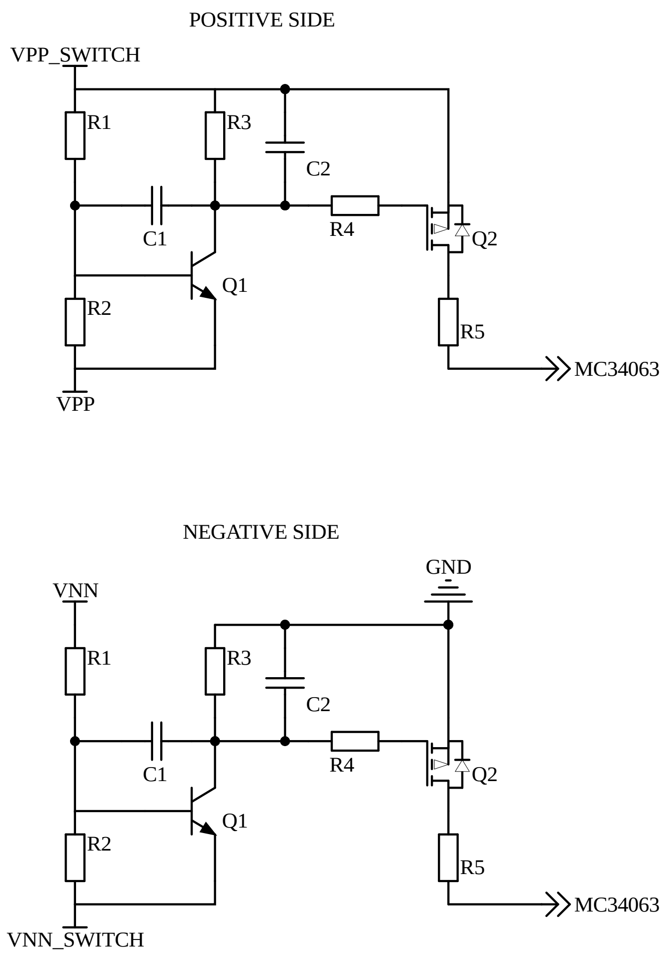
- $H_{FE}$ = 13
- $I_D$ = 23mA

## 5.3 Tracking Feedback

The LM317 and LM337 both require a maximum of 2V5 dropout.

Therefore, specify tracking voltage at ~~3V0~~ 4V0.

***The original 3V0 specification was revised to 4V0 following test results, as explained in §6.2.5.***




**CIRCUIT 4: TRACKING FEEDBACK CIRCUIT**

**Circuit Operation**

This circuit exploits the base emitter voltage of the BJT to be an approximate reference or “trigger” voltage. Below the trigger voltage, the BJT is non-conductive. Above the trigger, the BJT conducts. R1 and R2 then voltage divide the switching to linear regulator voltages to control the base voltage. The effects of base current are neglected.

The conduction from the BJT is used to trigger a P-MOSFET. R3 generates the gate voltage and is set to a sufficient value to produce the gate threshold voltage at negligible base current. It was not necessary to implement a voltage divider with R3 due to the sufficient rating of the MOSFET gate insulation. R4 protects the gate of the MOSFET from the numerous endpoints of the preceding net.

Capacitors C1 and C2 are added to allow for dampening. C1 exploits the Miller effect to filter high frequency feedback components. C2 simply slews the transition of Q2 into and out of conduction.

The output current is fed into the switching regulator feedback node (see Circuit 1and Circuit 2). In effect, once the tracking circuit triggers, the feedback node is injected with more current, which raises the feedback voltage, which appears as an increase in output voltage to the MC34063, causing the switching regulator to reduce the output voltage until the tracking circuit reaches some equilibrium with approximately 3V of tracking. R5 reduces the control authority of the tracking feedback path relative to the fixed voltage feedback path, essentially reducing the gain of the feedback path. By setting the two feedback resistors as equal, at full conduction of Q2 the feedback at most will imitate double the true switching regulator output voltage. If this were due to component failure, this would produce a fault condition of approximately ±5V output.

Due to the similar configuration of the MC34063 in the inverter and the booster converters, the same tracking feedback circuit is possible in both regulators. The only difference is the power source for the feedback current.

## 5.3.1 Component Selection

The SS8050 and LBSS84LT1G were arbitrarily selected as basic parts with sufficient operational ratings for this task.

The BJT, under these conditions, specifies:

- $V_{BE}$ = 0V7
- $h_{FE}$ = (120 ; 400)

## 5.3.2 Trigger Voltage Divider

For the 3V0 tracking and $V_{BE}$ = 0V7, the script in Appendix E resolved:

- $R_1$ = 27K
- $R_2$ = 8K2

## 5.3.3 Base Drive Current

$$I_{C_{MAX}} = \frac{V_{SR} - V_{LR} - V_{CE(SAT)}}{R_3} < \frac{V_{SR} - V_{LR}}{R_3}$$

$$I_{B_{MAX}} = \frac{I_C}{h_{FE}} \approx \frac{V_{SR} - V_{LR}}{h_{FE_{MIN}} R_3}$$

$$I_{BIAS} = I_A = \frac{V_{SR} - V_{LR}}{R_1 + R_2}$$

It is desirable to reduce the required base current to be a small fraction of the bias current to protect the assumption of neglecting the effects in bias current in setting the feedback trigger voltage divider. This can be achieved by increasing $R_3$ but should be limited so that small current effects do not falsely enable the MOSFET. Heuristically, the base current was limited to be less that 5% of the bias current.

Given that:

$$\left(\frac{I_{B_{MAX}}}{I_A}\right) = \frac{R_1 + R_2}{h_{FE_{MIN}} R_3}$$

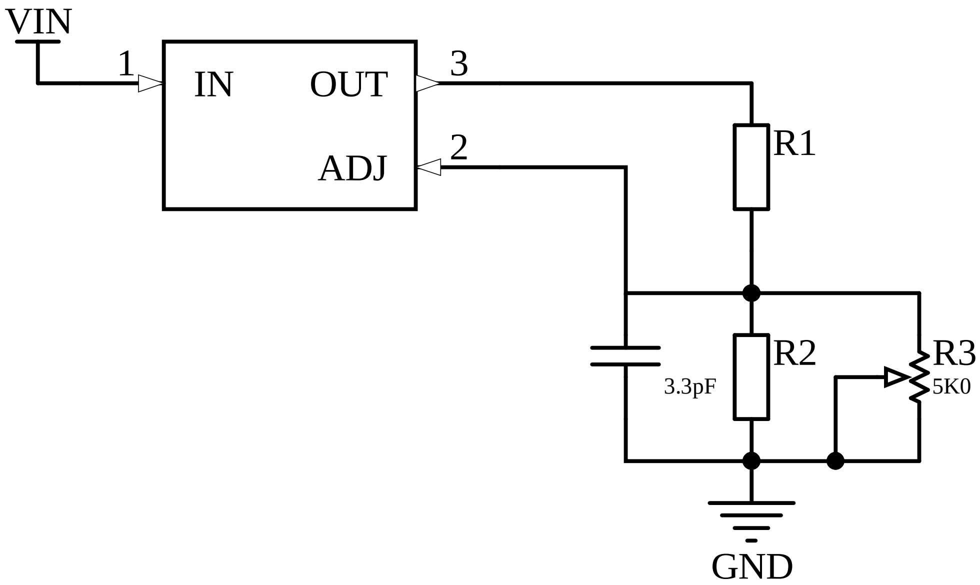
Through iteration over E12 values from 10K increasing, **27K** $\rightarrow \frac{I_{B_{MAX}}}{I_A} = 4\% < 5\%$.

## 5.4 Linear Regulator

The below applies to both the LM317 and LM337, which are functionally identical with regards to external components. These devices operate through the typical error amplifier with an internal reference voltage.

### 5.4.1 Voltage Adjustment

A 5K potentiometer was selected for user control.




**CIRCUIT 5: LINEAR REGULATOR FEEDBACK NETWORK**

The resistor to output uniquely determines the current through the feedback network at regulation.

Select $R_1$ = 240R (Recommended Value for 5.2mA Feedback Current)

A higher value in $R_1$ will produce a more linear radial response, however it is not advisable to deviate from the recommended value for this non-critical benefit.

R2 is introduced to limit the range of effect that R3 has to match the capable range of the switching regulator.

$$V_O = V_R \frac{R_2||R_3 + R_1}{R_1} + I_a R_2||R_3 \ (For\ Intransient\ Conditions)$$

The above relationship is plotted with various E12 values in R2. Per the below response, the following is observed:

2. Large values of $R_2$ result in a more constant rate of change in Output Voltage with $R_3$.
3. Large values of $R_2$ result in the output saturating before full rotation.

Achieving a full range in output with largest possible resistor is therefore the critical limiting factor. Given that:

$$V_{O_{MAX_{LR}}} = V_{O_{MAX_{SR}}} - V_{follow} = 13V75 - 3V0 = 10V75$$

Select $R_2$ = 2K7 ($V_{O\_MAX}$ = 10V47)

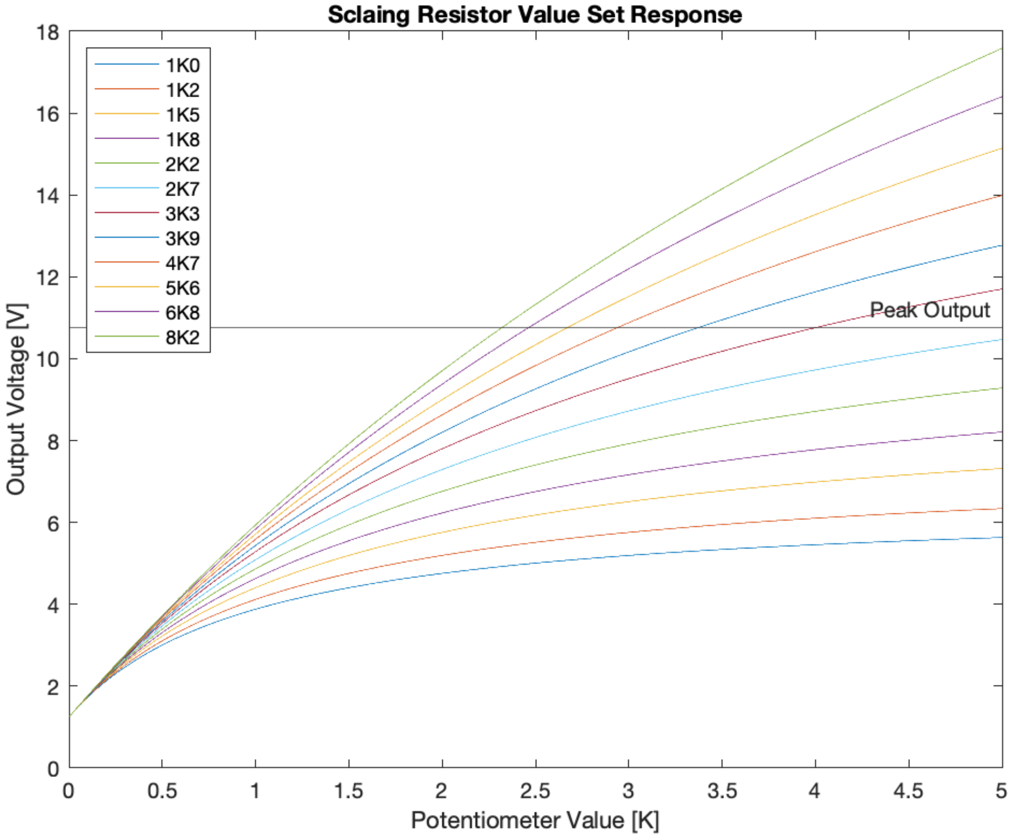



**FIGURE 3: LINEAR REGULATOR SCALING RESISTOR VALUE SELECTION**

### 5.4.2 Feedback Capacitor

A feedback capacitor is added to suppress any electromechanical transconductance due to the potentiometer.

Via the way of the Norton Equivalent circuit, with the potentiometer being the load:

$$I_N = \frac{V_R}{R_1} = 5.4mA$$

$$R_N = \frac{R_2}{(R_1 + R_2) + sR_1R_2C}\frac{R_1}{V_R}$$

Therefore, a 3.3pF capacitor results in a -3dB bandwidth at approximately 20kHz, which should suppress most noise while retaining a nominal dynamic response for the typical device output loads.

### 5.4.3 Output Capacitor

Select 1uF 50V 0805 MLCC. This follows the typical application circuit.

### 5.4.4 Input Capacitor

A 100nF 50V 0805 MLCC is placed in case of any need for input capacitance but is not populated.

## 5.5 LED Indicators

The LEDs are valuable user feedback indicators but represent a significant power draw. It would be wasteful to drive these LEDs directly off each output rail, and (with simple resistive current limiting) would result in variable brightness with voltage adjustment.

Therefore, effort must be made to activate LEDs using sensing circuitry that would source illumination current from the 5V input.

A prior circuit attempted to enable the LED based triggering a MOSFET using the linear regulator reference voltage. In Revision 2.0, this was a success on the positive rail, but failed on the negative rail, due to the different gate threshold voltages between the P and N MOSFETS needed on each rail. In order to avoid relying on this imprecise characteristic, a comparative circuit was specified.

### 5.5.1 LED Current

Select Greed LED: 19-217/GHC-YR1S2/3T

- $V_F$ = 3V3
- $I_{MAX}$ = 25mA

Set $I_{LED}$ = 5mA

$$R_{LED} = \frac{V_{CC} - V_F}{I_{LED}} = \frac{5V0 - 3V3}{5mA} = 340R \ \approx 330R$$

$$\therefore I_{LED} = \frac{5V0 - 3V3}{330R} = 5.15mA$$

Since all LEDs are driven off 5V, this remains a common series resistor value between all indicators.

### 5.5.2 Op-Amp Selection

Select Op-Amp: LMV321IDBVR

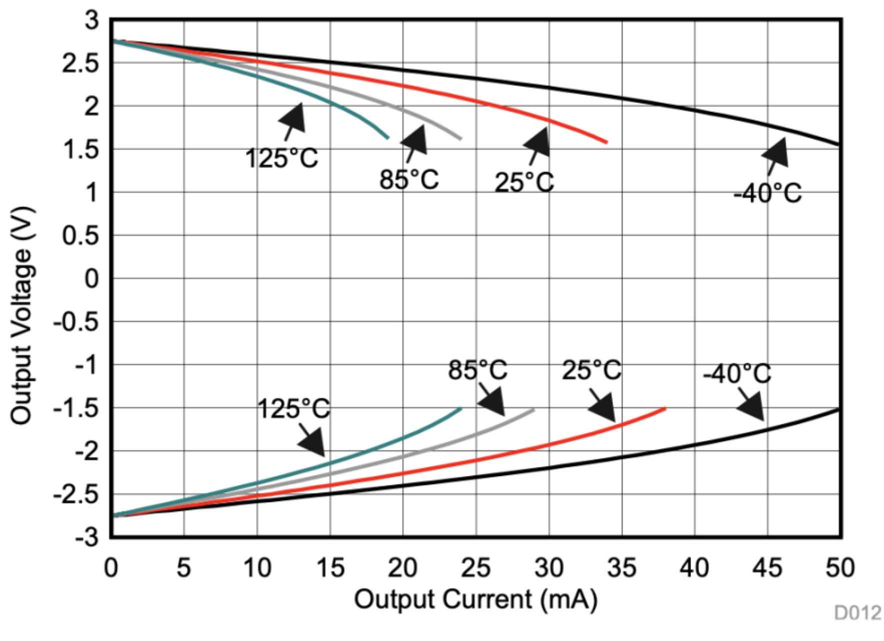
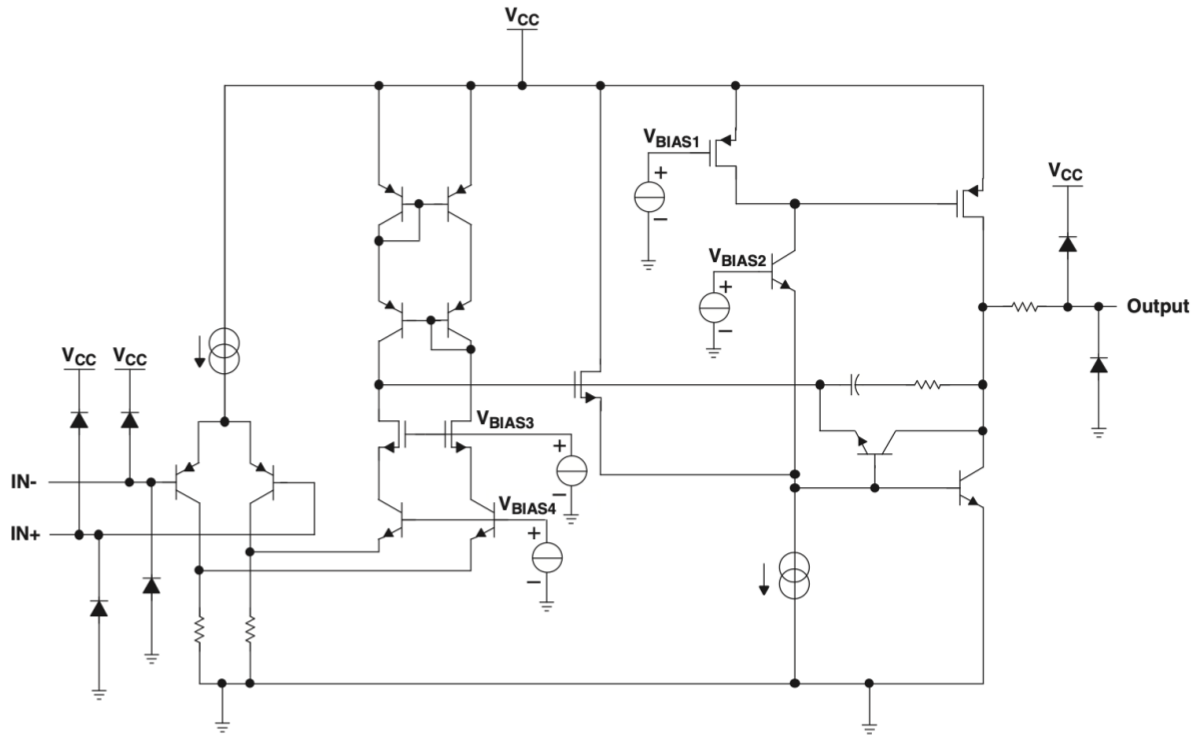



**FIGURE 4: LMV321 CLAW**

$V_{CC}$ = 5V5. Source: Texas Instruments




**CIRCUIT 6: LMV321 FUNCTIONAL CIRCUIT DIAGRAM**
Source: Texas Instruments

This op-amp was selected predominantly for it’s SOT-23-5 package. The rail-to-rail operation is also beneficial, but only in terms of simplifying the mathematics to follow.

The following critical limitations of the LMV321 should be acknowledged:

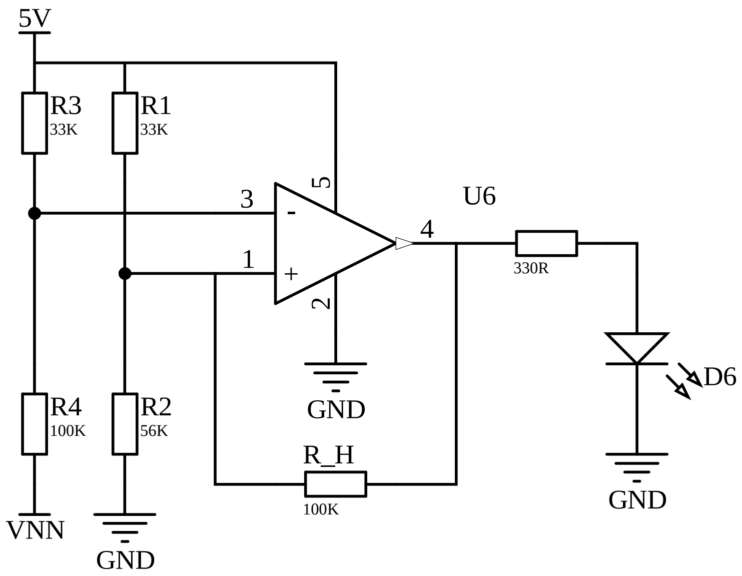
1. $V_{CC\_MAX}$ = 5V5
2. NOT short circuit to $V_{CC}$ protected.
3. $V_{IO}$ < 7mV
4. $I_{IB}$ < 250nA

From the above information, the following can be determined:

1. Operation off 5V is prescribed (as was intended).
2. The inputs must strictly remain within 0 to 5V.
3. The op-amp should source current, not sink, to the LED (both options are technically possible).
4. The input offset voltage need not be compensated for in trigger threshold definitions.
5. The input bias current is negligible for 10’s of K peripheral resistors.
6. At 5.15mA output current drive, ideal rail-to-rail performance can be approximated.

The derivations to follow assume the above.

### 5.5.3 Negative Rail Indicator




**CIRCUIT 7: NEGATIVE RAIL LED INDICATOR HYSTERESIS CIRCUIT**

**Circuit Description**

This circuit achieves the following goals:

1. Op-amp operation off the 5V supply.
2. Reliable, precisely programable triggering levels and hysteresis window.
3. Cheap, compact components.
4. Direct LED drive off the op-amp output.
5. Negligible loading of the output rail.
6. Reliable restriction of $V_-$ to be above 0V.

The negative rail's voltage is sensed relative to 5V through the voltage divider, which limits the sensed voltage to remain above 0V, given a minimum output voltage. This voltage is compared to a 5V referenced threshold. This threshold is programmed with hysteresis though the positive feedback resistor to correlate to a set of two possible threshold conditions, based on the state of the output.

The LMV321 is capable of driving the LED directly given the set 5.15mA drive current. Regardless, this device is indefinitely tolerant to short circuit conditions to ground.

**Triggering Specifications**

- $V_{NN\_ON}$ = -5V (Nominal good-inversion threshold)
- $V_{NN\_OFF}$ = -1V5 (Just above point of minimum regulation)

**Circuit Equations**

$$V_- = \frac{(5V - V_{NN})R_4}{R_3 + R_4} + V_{NN}$$

$$V_+ = \begin{cases} 5V\dfrac{R_2}{R_1||R_H + R_2} & V_O = HIGH\ (5V) \\ 5V\dfrac{R_2||R_H}{R_1 + R_2||R_H} & V_0 = LOW\ (0V) \end{cases}$$

**Constraints**

1. $V_- > 0V$
2. $V_{+\_LOW\_TH} \rightarrow V_{NN} = -5V$
3. $V_{+\_HIGH\_TH} \rightarrow V_{NN} = -1V5$

**Sense Divider**

$$\therefore Let\ V_- = 0V\ @\ V_{NN_{MIN}} = -15V\ (-13V75 - 1V25\ Margin)$$

This maximises the usable range within reasonable safety.

Using the script in Appendix E, the following values were resolved:

- $R_3 = 33K$
- $R_4 = 100K$

**Upwards Crossing Threshold ($V_O$ Starts LOW)**

- $V_{NN} = -5V$

$$V_- = \left(5V - (-5V)\right)\frac{100}{133} + (-5V) = 2V519 = V_{+_{LOW}}$$

$$\therefore 2V519 = 5V\frac{R_2||R_H}{R_1 + R_2||R_H}$$

**Downwards Crossing Threshold ($V_O$ Starts HIGH)**

- $V_{NN} = -1V5$

$$V_- = \left(5V - (-1V5)\right)\frac{100}{133} + (-1V5) = 3V387 = V_{+_{HIGH}}$$

$$\therefore 3V387 = 5V\frac{R_2}{R_1||R_H + R_2}$$

**Simultaneous Equations**

$$\frac{2V519}{5V} = \frac{R_2||R_H}{R_1 + R_2||R_H} = \frac{R_2R_H}{R_1R_2 + R_1R_H + R_2R_H}$$

$$\frac{3V387}{5V} = \frac{R_2}{R_1||R_H + R_2} = \frac{R_1R_H + R_2R_H}{R_1R_2 + R_1R_H + R_2R_H}$$

Acknowledge the common denominator.

$$\therefore \frac{2V519}{3V387} = \frac{R_2R_H}{R_1R_2 + R_2R_H} = \frac{R_H}{R_1 + R_H}$$

Using the script in Appendix E, the following values were resolved:

- $R_1 = 33K$
- $R_H = 100K$

**Back Substitution**

$$3V387 = 5V\frac{R_2}{R_1||R_H + R_2} \rightarrow R_2 = 52K10 \approx 47K$$

(56K rounding results in rejected $V_{+\_HIGH}$ result as was discovered during an iteration of Verification)

**Verification**

$$V_{+_{LOW}} = 5V\frac{56K||100K}{56K||100K + 33K} = 2V605 \rightarrow V_{NN} = -4V65$$

Result is accepted.

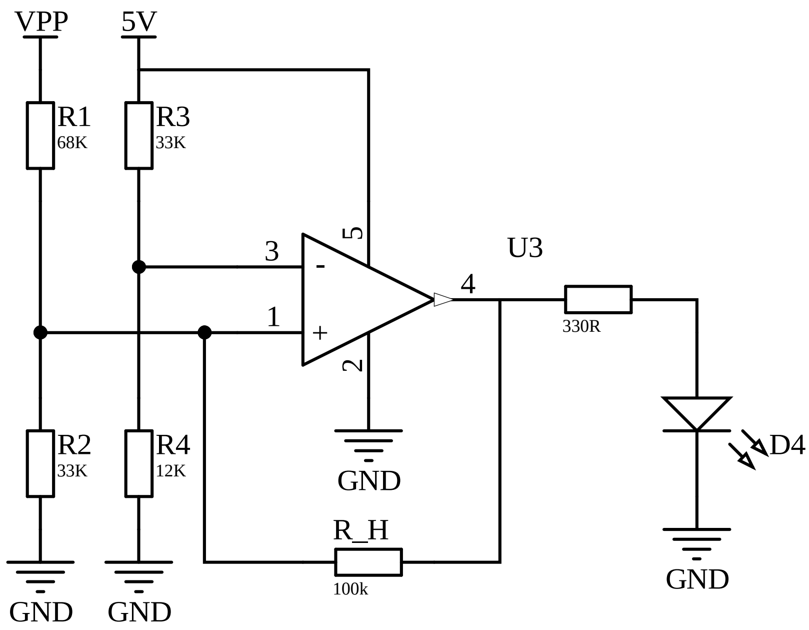
$$V_{+_{HIGH}} = 5V\frac{56K}{56K + 100K||33K} = 3V465 \rightarrow V_{NN} = -1V18$$

Note: This result is technically 20mV below the minimum output voltage of the LM337. However, due to the zero LMV312 headroom loss assumption, this result is an underestimate, and therefore it is expected that in reality the device will indeed trigger off.

The result is accepted.

Therefore, the overall circuit is accepted.

### 5.5.4 Positive Rail Indicator




**CIRCUIT 8: POSITIVE RAIL LED INDICATOR HYSTERESIS CIRCUIT**

**Circuit Description**

This circuit is functionally similar to Circuit 7, but with the following key differences:

1. Hysteresis is applied to the voltage-sensing divider, since the polarity of transitions are inverted relative to Circuit 7.
2. The negative input is set to a fixed value.

Unfortunately, this results in different — although similar — circuit derivations.

**Triggering Specifications**

- $V_{PP\_ON} = 5V$
- $V_{PP\_OFF} = 1V5$

**Circuit Equations**

$$V_- = 5V \frac{R_4}{R_3 + R_4}$$

$$V_+ = \begin{cases} \left(\frac{V_{PP}}{R_1} + \frac{5V}{R_H}\right) R_1||R_2||R_3 & V_O = HIGH\ (5V) \\ \left(\frac{V_{PP}}{R_1}\right) R_1||R_2||R_3 & V_O = LOW\ (0V) \end{cases}$$

**Constraints**

1. $V_+ < 5V$
2. $V_{+\_LOW} = V_-$ @ $V_{PP} = 5V$
3. $V_{+\_HIGH} = V_-$ @ $V_{PP} = 1V5$

**Sensing Divider**

$$Let\ V_{+_{HIGH}} = 5V\ @\ V_{PP} = 15V\ (13V75 + 1V25\ Margin)$$

$$\therefore 5V0 = \left(\frac{15V}{R_1} + \frac{5V0}{R_H}\right) R_1||R_2||R_3 \rightarrow 5V0 = 15V \frac{R_2}{R_1 + R_2} (R_H\ is\ not\ conducting\ current)$$

Therefore, the script in Appendix E resolved the following values:

- $R_1$ = 68K
- $R_2$ = 33K

**Upwards Crossing Threshold ($V_O$ is LOW)**

$$V_{+_{LOW_{TH}}} = \frac{5V0}{R_1} R_1||R_2||R_3 = V_-$$

**Downwards Crossing Threshold ($V_O$ is HIGH)**

$$V_{+_{HIGH_{TH}}} = \left(\frac{1V5}{R_1} + \frac{5V0}{R_H}\right) R_1||R_2||R_3 = V_-$$

**Simultaneous Equations**

$$\left(\frac{1V5}{R_1} + \frac{5V0}{R_H}\right) R_1||R_2||R_3 = \frac{5V0}{R_1} R_1||R_2||R_3 \rightarrow R_H = \frac{5V0}{5V0 - 1V5} R_1 = 97K \approx 100K$$

**Fixed Reference**

$$V_{+_{LOW_{TH}}} = \frac{5V0}{R_1} \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_2 + R_2 R_H} = 1V337$$

$$\therefore 1V337 = 5V0 \frac{R_4}{R_3 + R_4}$$

The script in Appendix E resolved:

- $R_3$ = 33K
- $R_4$ = 12K

**Verification**

$$1V337 = \frac{V_{PP}}{68K} 68K\Big|\big|33K\big|\Big|100K \rightarrow V_{PP} = 4V98$$

$$1V337 = \left(\frac{V_{PP}}{68K} + \frac{5V0}{100K}\right) 68K\Big|\big|33K\big|\Big|100K \rightarrow V_{PP} = 1V58$$

Both results above are accepted, therefore the circuit overall is accepted.

# 6 Test Results

## 6.1 Test Parameters

### 6.1.1 Default Testing Methods

Unless stated otherwise, all tests were —:

- conducted at uncontrolled room temperature.
- under uncontrolled but noncondensing humidity.
- conducted on a single board per test, which may be interchanged between different tests.

For the purposes of these tests, minimum voltage means the voltage closest to ground. i.e. the minimum arithmetic absolute.

### 6.1.2 Device Under Test

The tests were conducted on the following device and revision:

TABLE 1: DUT INFORMATION

| | |
|---|---|
| **Project** | SIO2MKR |
| **Project Revision** | v3.0 |
| **Release Date** | 5 August 2021 |
| **Manufacturer** | JLCPCB |
| **Manufacture Date** | October 2021 |
| **Order No.** | 2483764E_Y163-211019 |

### 6.1.3 Test Equipment

The following test equipment was used in performing these tests:

TABLE 2: TEST EQUIPMENT

| Device | Model | Serial Number |
|---|---|---|
| Oscilloscope | Keysight EDUX1002G | CN57202104 |
| DC Power Supply | Keysight E3630A | KR72911794 |
| DC Power Supply | MCP M10-QD 3020 | 17120014 |
| Battery Bank | Romoss Solo 5 | 1610017083 |
| Multimeter | Fluke 175 | 41170073 |
| Multimeter | Keysight U1232A | MY58210030 |

Note: All devices branded under HP or Agilent are stated here as Keysight.

## 6.2 Functional Tests

### 6.2.1 Power Switch

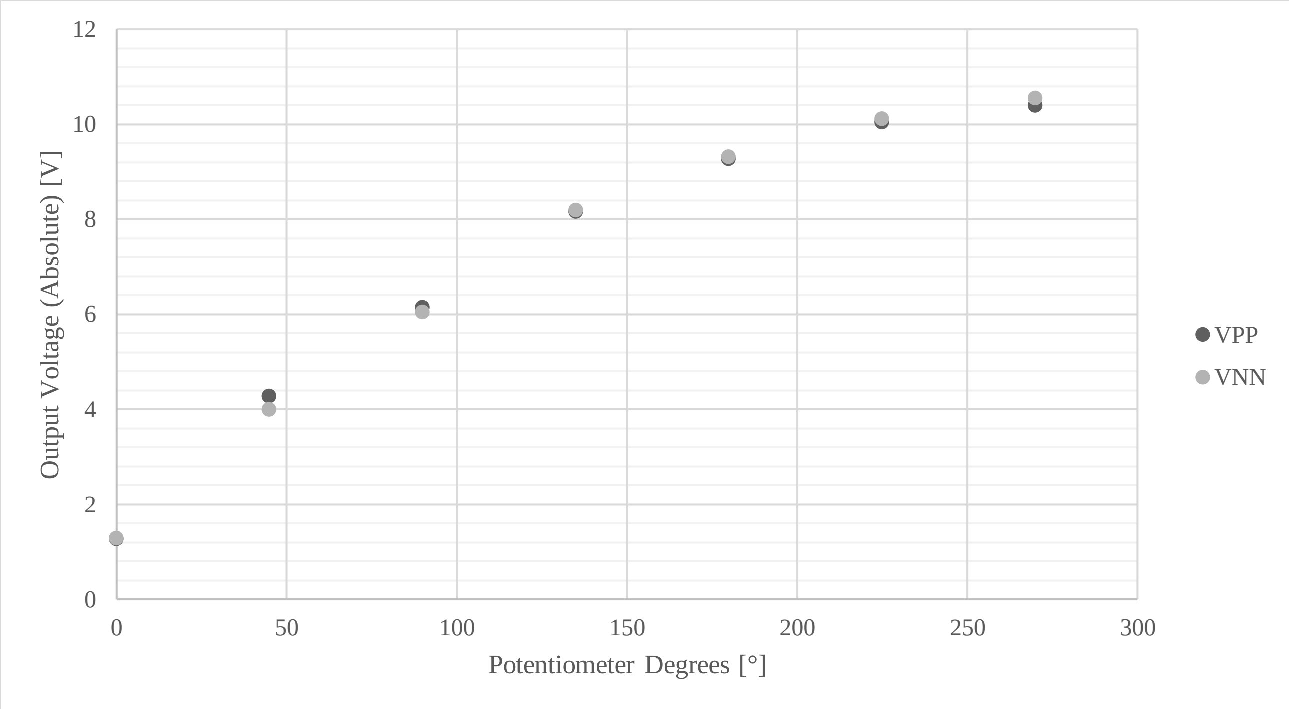
| | |
|---|---|
| **Test Description** | Power is applied. The slide switch is moved to the on position and then back to the off. |
| **Pass Criteria** | The 5V LED must be on when the switch is on and off when the switch is off. |
| **Test Result** | PASS |

### 6.2.2 Power LEDs

| | | | |
|---|---|---|---|
| **Test Description** | The device is turned on with both potentiometers set to the minimum output. The voltage is then increased on both rails until the indicator LEDs toggle on. The voltage is then decreased until the LEDs toggle off (through the hysteresis band). These thresholds are measured. | | |
| **Pass Criteria** | Toggling within 10% ±0V2 of the design criteria: [-1V5, -5V0] and [1V5, 5V0] | | |
| **Results** | **Side** | **On Threshold** | **Off Threshold** |
| | Positive Side | 5V015 | 1V780 |
| | Negative Side | -4V703 | -1V412 |
| **Test Result** | PASS | | |

### 6.2.3 Voltage Adjustment

| | |
|---|---|
| **Test Description** | The device was designed for a semi linear voltage response to adjustment on the potentiometers. It is observed that the potentiometers have an approximately 270° full range. Assuming the potentiometers are linear in their response, the response may be mapped through the range of revolution to evaluate the effectiveness of the compensation. |
| **Pass Criteria** | None. For Information only |
| **Results** | Refer to figure below. |
| **Test Result** | N/A |




### 6.2.4 Fuses

| | |
|---|---|
| **Test Description** | With the 5V output shorted to GND, the PTC bypass jumper closed, and with power injected directly upon the input side of the fuse (with a soldered wire) — power is applied using the MCP M10 supply. With the power switch open, the voltage is set to 5V with the current limit set to 0A. The switch is closed. Thereafter, the current limit is removed and increased rapidly to approximately 6A. |
| **Pass Criteria** | The fuse must open. |
| **Observations** | The fuse did not blow. Instead, the MOSFET switch experienced intense heating, and proceeded to melt. The fuse began it heat, but de-soldered, releasing the injecting wire, and thereby ending the test.<br>The test also melted some plastic pieces on connecting wires due to poor connector resistance. This test indicates that the fuse fails to protect at least one critical device, the power switch MOSFET, from heat destruction, and therefore the system is insufficiently protected. |
| **Actions** | The fuse must be replaced with a lower current alternative, recommended as 1-1.5A. Due to the typical contact resistances encountered in breadboard prototyping, there is no conceivable application that would require more than this this amount of current without causing destruction to the breadboard, as was observed, hence this recommended rating.<br>This test should ideally be repeated with a new fuse rating. |
| **Test Result** | FAIL |

| | | |
|---|---|---|
| **Test Description** | The 5V output is connected to a 1R load to GND, the PTC bypass jumper is open, and normal power inputted via a 15W/5V USB supply. The true resistance (including connector resistance) is measured using a multimeter, compensated for the lead resistance. The power switch is closed, and the output voltage is measured. The input power supply is expected to regulate to a maximum of 3A output, and so the output voltage is expected to be below 5V, however if the PTC fuse opens, this will correspond to a further voltage drop some appreciable time after the switch was opened. | |
| **Pass Criteria** | The fuse must open. | |
| **Measurements** | True Load | 1R5 |
| | Initial Output Voltage | 1V |
| | Steady State Output Voltage | 240mV |
| **Observations** | The output voltage briefly increased to approximately 1V, but within 2s decreased to 240mV. With the load impedance, this corresponds to an initial current of at least 660mA, in excess of the PTC fuse's rating. This rapid decrease therefore corresponds to an upstream device increasing its impedance. With the only upstream devices being the 3A fuse, power switch MOSFET, USB connector and the input supply, which are all rated to conduct in excess of 3A, it is therefore assumed that the PTC was indeed responsible for this action. The steady state output voltage therefore corresponds to 160mA/38mW output, which is regarded as being a suitably safe value. | |
| **Test Result** | PASS | |

### 6.2.5 Tracking Feedback

| | |
|---|---|
| **Test Description** | The switching regulator output and linear regulator output voltages are monitored by an oscilloscope with a rolling acquisition. A mathematical function is also plotted for the difference between the two inputs. It is expected that the switching rail tracks the linear rail with a constant 3V differential, with a minimum limit of 5V in the case of the positive regulator. The output voltage is adjusted through the full range to demonstrate the tracking function. The test is repeated for both positive and negative sides. |
| **Pass Criteria** | Tracking Voltage > Maximum Dropout Voltage (2V5) |
| **Results** | See figure below. |
| **Observations** | The tracking feedback is functionally correct but fails to maintain the desired minimum tracking voltage, maintaining approximately 2V2 tracking voltage on both sides. Upon review of the calculations, it is believed that a combination of a lower-than-expected base-emitter voltage, and the expected base drive current drop was responsible. |
| **Actions** | The calculations were revised, given these measurements, in an identical manner upon the basis of a 4V0 tracking voltage. If whatever effects remain linear through this change, this basis is expected to produce the intended tracking voltage of 3V.<br>This change should also improve the performance of the device. |
| **Test Result** | FAIL |

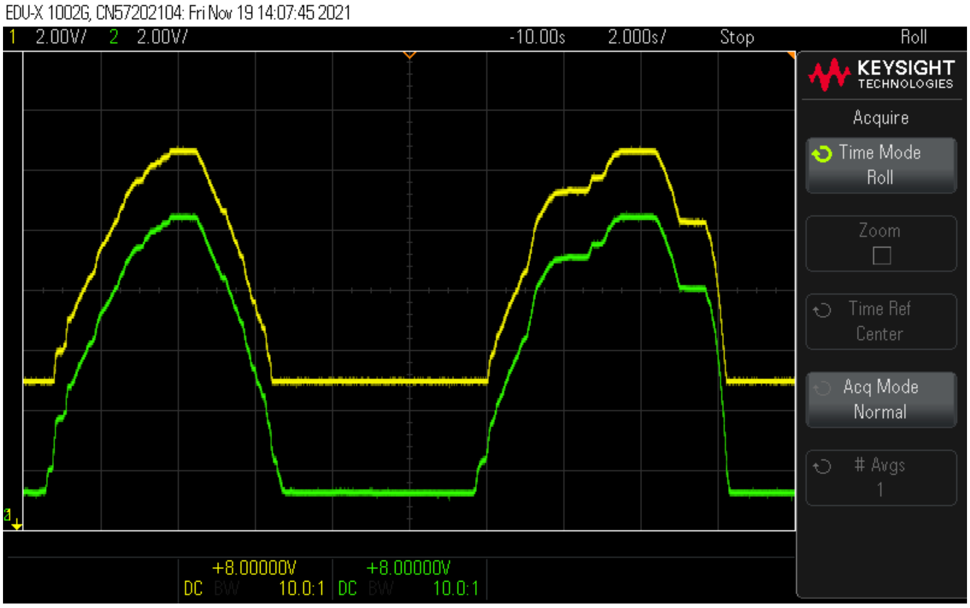



**FIGURE 5: POSITIVE SIDE VOLTAGE TRACKING**

The voltage tracking feedback directs the boosting switching regulator output (yellow) to maintain a fixed voltage difference of approximately 3V from the linear regulator's output (green). At 5V, the inrush diode holds the switching output at 5V.

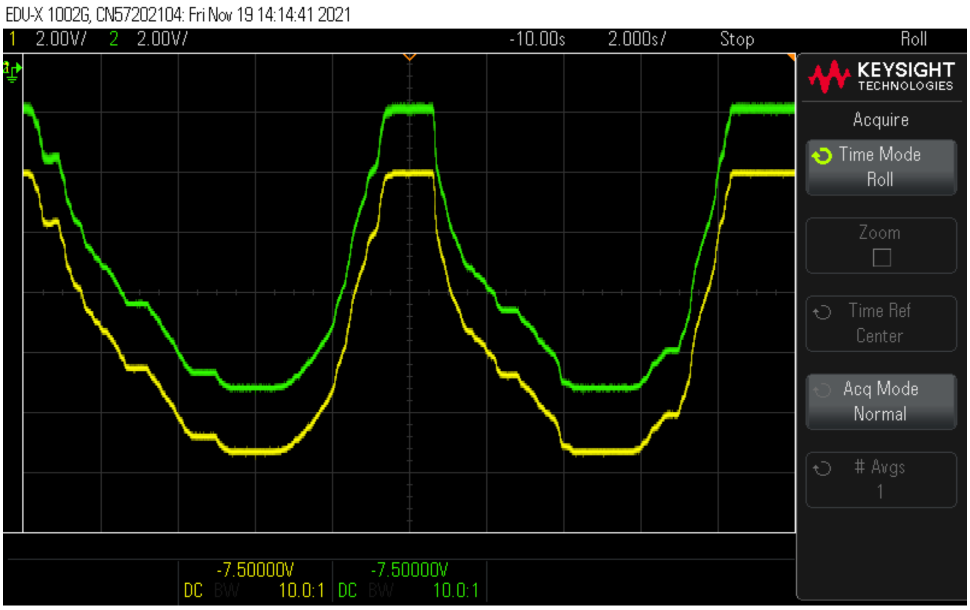



**FIGURE 6: NEGATIVE SIDE VOLTAGE TRACKING**

Similar to the positive side; the voltage tracking feedback directs the inverting switching regulator output (yellow) to maintain a fixed voltage difference of approximately -3V from the linear regulator's output (green). In this circuit there is no inrush diode, and so the voltage tracking is maintained throughout the range of output.

## 6.3 Static Characteristics

### 6.3.1 Output Range

| | | | |
|---|---|---|---|
| **Test Description** | Measure the full range of output voltage at no load. | | |
| **Pass Criteria** | Output ranging over ±(1V2, 10V5) | | |
| **Results** | | **Minimum** | **Maximum** |
| | **Positive Side** | 1V264 | 10V48 |
| | **Negative Side** | -1V298 | 10V63 |
| **Test Result** | PASS | | |

### 6.3.2 Peak Output Current and Power

| | | |
|---|---|---|
| **Test Description** | At no load output voltage of ±10V5, measure the -3dB voltage (7V42) load current using the circuit shown below. | |
| **Pass Criteria** | -3dB Load Current > 40mA | |
| **Results** | | **-3dB Load Current** |
| | **Positive Side** | 180mA |
| | **Negative Side** | 85mA |
| **Test Result** | PASS | |

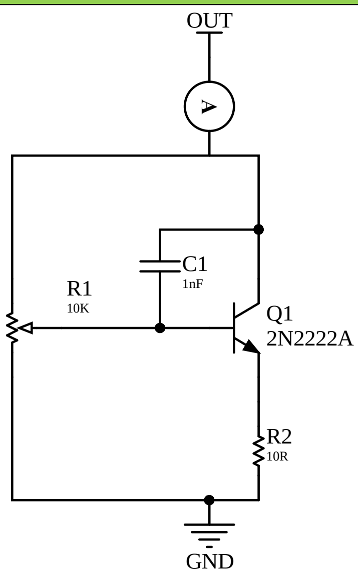



**FIGURE 7: ADJUSTABLE CURRENT LOAD**

This circuit adjusts the BJT in a common emitter configuration with a variable bias from the potentiometer. The power is dissipated by either the BJT or the resistor, depending on the bias point. The capacitor dampens the BJT to slow any change in conductance.
When testing the negative side, GND is replaced with out and vice versa.

## 6.4 Dynamic Characteristics

### 6.4.1 Load Regulation

| | | | | |
|---|---|---|---|---|
| **Test Description** | At maximum output voltage and for both sides, step from a 560R to a 280R (560R‖560R) load to ground and measure the change in output voltage after the output voltage has fully stabilised. | | | |
| **Pass Criteria** | <1% Output Voltage Change | | | |
| **Results** | | **560R Voltage** | **280R Load Voltage** | **Change** |
| | **Positive Side** | 10V5366 | 10V5772 | +0.39% |
| | **Negative Side** | -10v5893 | -10V5340 | -0.52% |
| **Test Result** | PASS | | | |

### 6.4.2 Line Regulation

As the input voltage is already sourced via a regulated USB supply, and the performance of the tracking pre-regulator, this test was omitted as an unlikely test case.

### 6.4.3 Transient Recovery

| | | | | | |
|---|---|---|---|---|---|
| **Test Condition** | At 9V output voltage, step from a 1K to 91R (1K ‖ 100R) load and then back again. Observe the step response of the output voltage and measure the time to settle back to within 15mV of the starting output voltage and the peak dropout. | | | | |
| **Pass Criteria** | As specified in the respective datasheets for the LM337 and LM317. | | | | |
| **Results** | | **Step Up Settling Time** | **Step Up Undershoot** | **Step Down Overshoot** | **Step Down Settling Time** |
| | **Positive Side** | 160us | 300mV | 400us | 350mV |
| | **Negative Side** | 175mV | 20us | 40us | 100mV |
| **Test Result** | PASS | | | | |

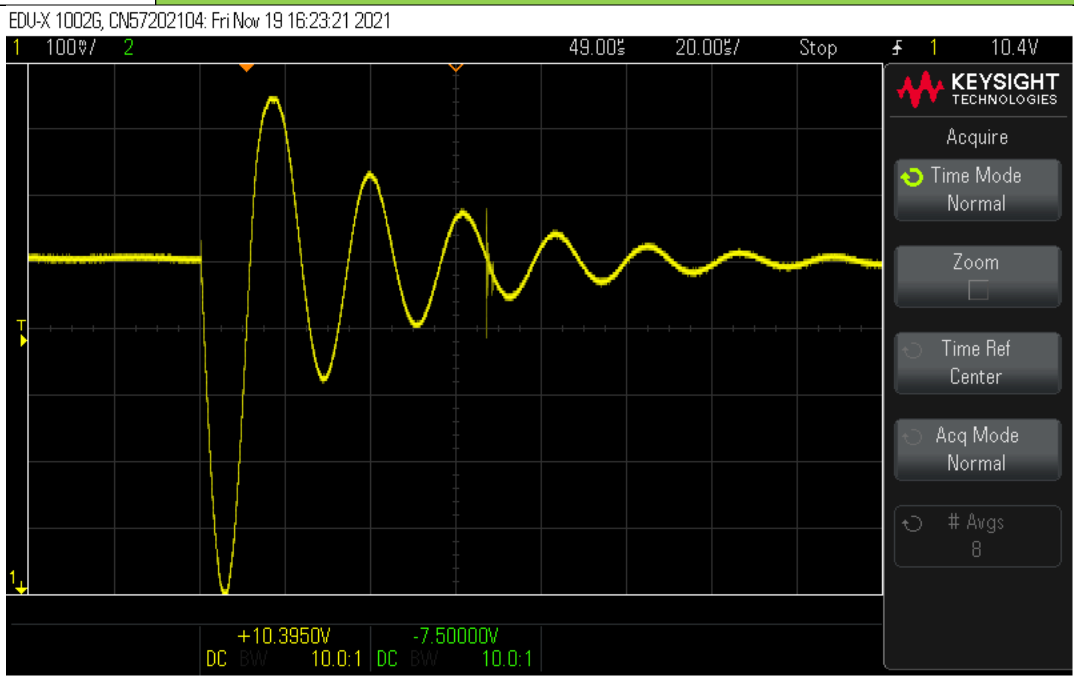



**FIGURE 8: POSITIVE SIDE STEP UP TRANSIENT RESPONSE**

The positive side experiences a strong second order response. The output settles to within 15mV by 160us with a 300mV undershoot. This response is largely determined by the LM317 linear regulator. The minor spite towards the centre is unfiltered switching noise from the 5V source.

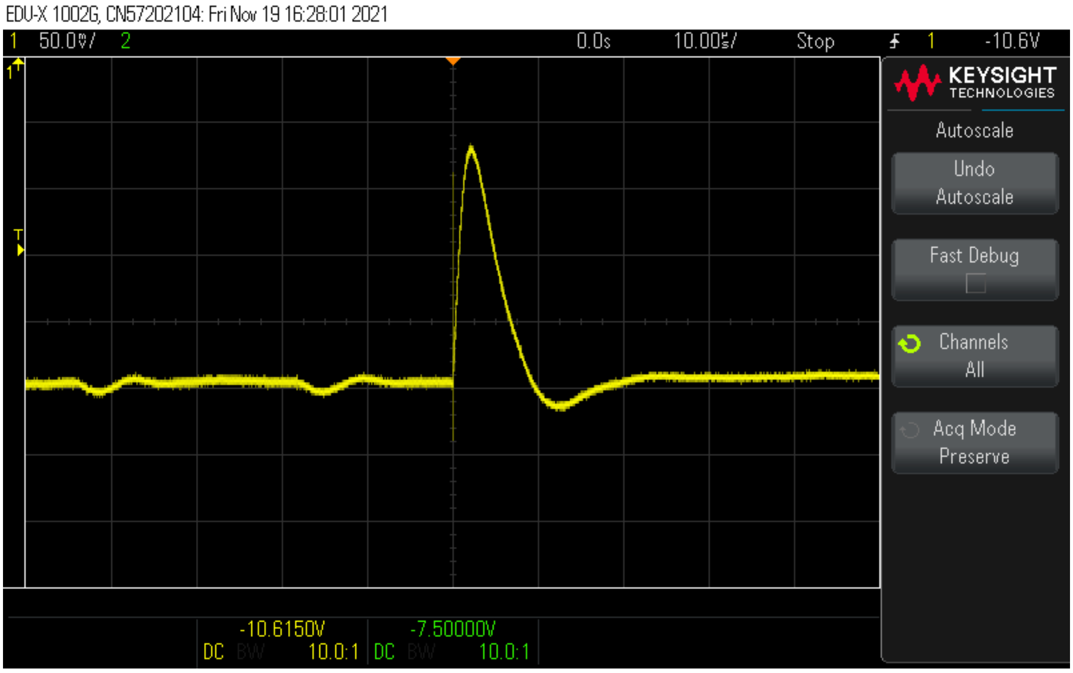



**FIGURE 9: NEGATIVE SIDE STEP UP TRANSIENT RESPONSE**

The LM337 produces a much more dampened response than the LM317, settling to within 15mV by 20us, with a 175mV undershoot. The very sharp initial spike is due to parasitic source inductance in the measurement and should be ignored.

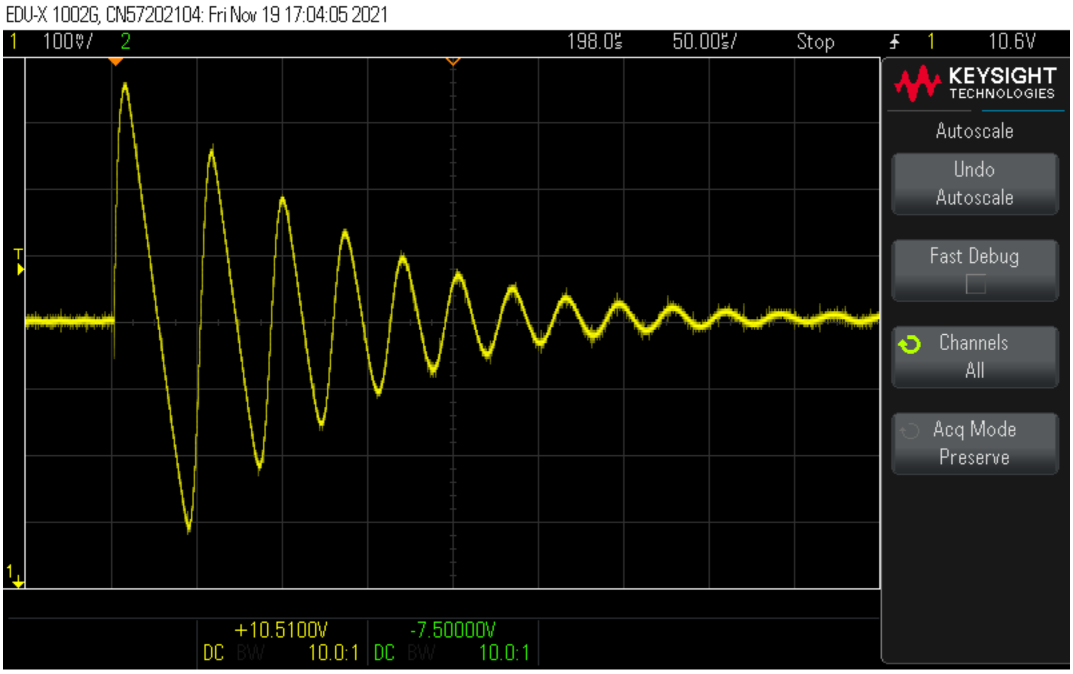



**FIGURE 10: POSITIVE SIDE STEP DOWN TRANSIENT RESPONSE**

The posive side responds with a similar step down response as the step up. The output settles within 400us with a peak overshoot of 350mV.

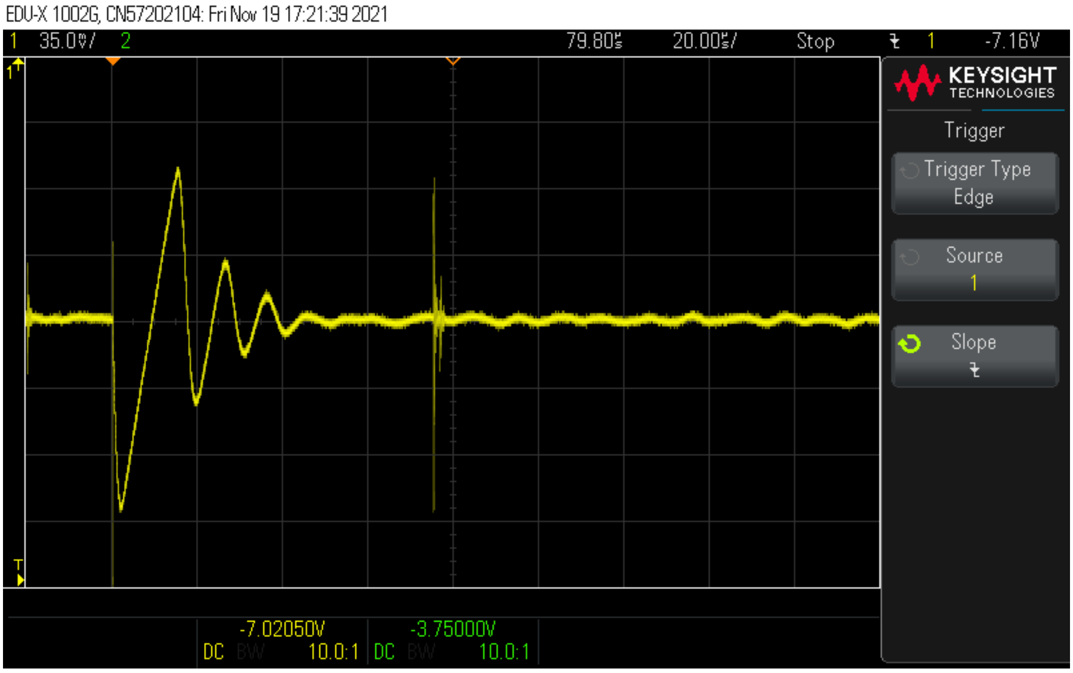



**FIGURE 11: NEGATIVE SIDE STEP DOWN TRANSIENT RESPONSE**

The negative side step down exhibits an asymmetrical second order response. Regardless, the output settles within 40us with a peak overshoot of 100mV.

### 6.4.4 Output Ripple and Noise

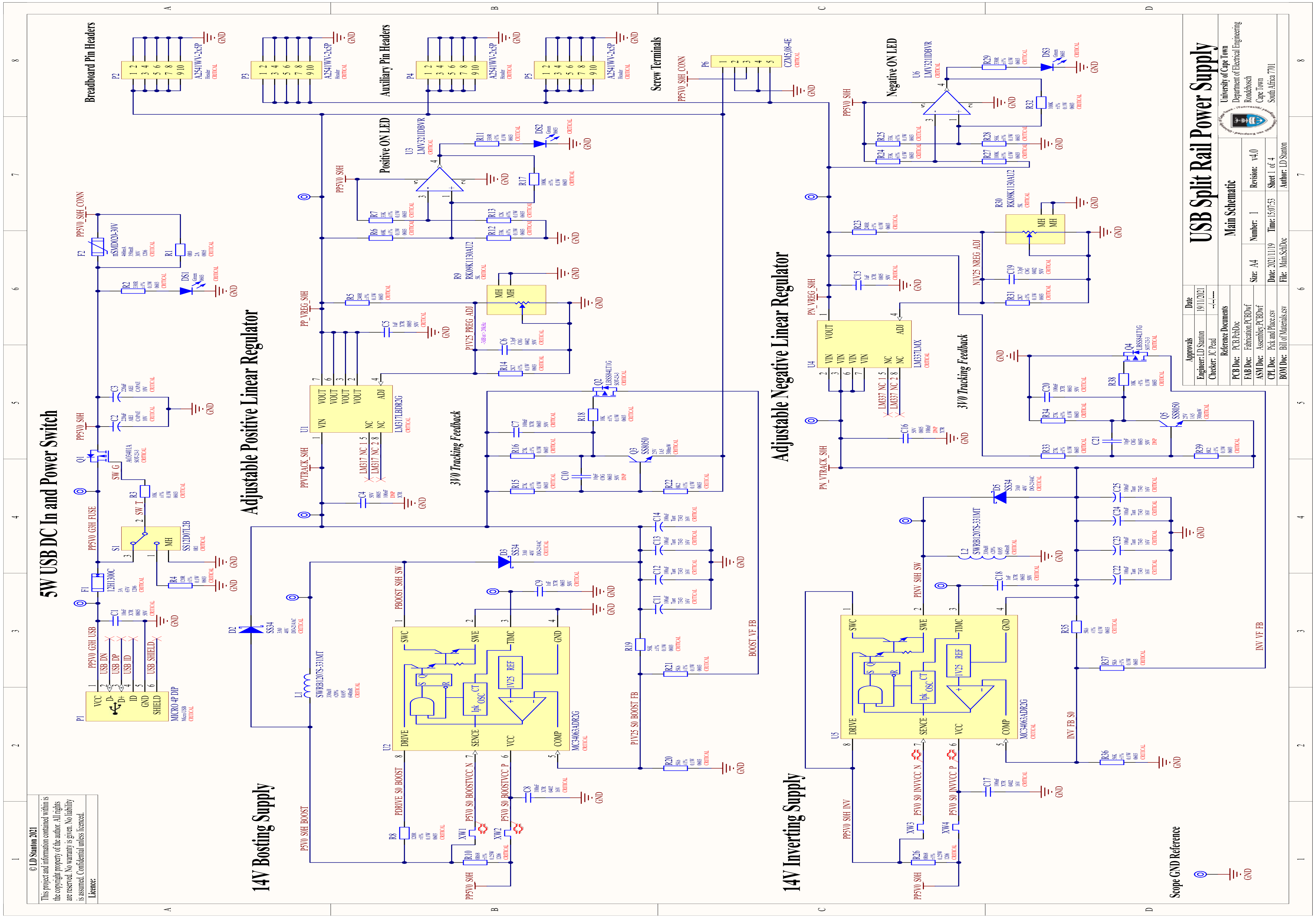
| | | | |
|---|---|---|---|
| **Test Condition** | At maximum output voltage, power input by a portable USB battery bank, and at a 1K load, measure the output AC RMS noise and Peak-to-Peak ripple over a 1ms period. | | |
| **Pass Criteria** | < 5mVrms, < 50mVpp | | |
| **Results** | | **AC RMS** | **Ripple Peak to Peak** |
| | **Positive Side** | 1.86mVrms | 48mVpp |
| | **Negative Side** | 2.99mVrms | 36mVpp |
| **Test Result** | PASS | | |

## 6.5 Supplemental Information

**TABLE 3: SUPPLEMENTAL INFORMATION**

| | |
|---|---|
| **Outer Dimensions** | 5.2 x 6.4 x 2.5mm |
| **Weight** | |

# Appendix A — Schematic



# Appendix D — Bill of Materials

| Comment | Description | Designator | QTY | LCSC Part Number |
|---|---|---|---|---|
| CL21B103KBANNNC | MLCC 10nF 0805 50V X7R ±10% | C1 | 1 | C1710 |
| RVT1A221M0605 | Aluminium Electrolytic Capacitor 220uF CAPAE 10V ±20% | C2, C3 | 2 | C3345 |
| CC0805KRX7R9BB104 | MLCC 100nF 50V 0805 X7R ±10% | C4, C16 | 2 | C49678 |
| CL21B105KBFNNNE | MLCC 1uF 0805 50V X7R ±10% | C5, C15 | 2 | C28323 |
| 0402CG3R3C500NT | MLCC 3.3pF 0402 50V C0G ±0.25pF | C6, C19 | 2 | C1565 |
| CC0603KRX7R9BB104 | MLCC 100nF 50V 0603 X7R ±10% | C7, C20 | 2 | C14663 |
| CL05B104KO5NNNC | MLCC 100nF 0402 16V X7R ±10% | C8, C17 | 2 | C1525 |
| CL10B102KB8NNNC | MLCC 1nF 0603 50V X7R ±10% | C9, C18 | 2 | C1588 |
| MLCC 10pF 0603 50V C0G | MLCC 10pF 0603 C0G ±0.1pF | C10, C21 | 2 | C1634 |
| 293D107X9016D2TE3 | Tantalum Capacitor 100uF 16V ±20% | C11, C12, C13, C14, C22, C23, C24, C25 | 8 | C129696 |
| 19-217/GHC-YR1S2/3T | LED 0603 SMT Green | D1, D4, D6 | 3 | C72043 |
| SS34 | Schottky Barrier Diode 40V 3A0 550mV | D2, D3, D5 | 3 | C8678 |
| 12H1300C | Fuse SMD Slow Blow 3A 63VAC 1206 | F1 | 1 | C182445 |
| nSMD020-30V | Fuse SMD PTC Resettable 460mA 30VDC 1206 | F2 | 1 | C69680 |
| SWRB1207S-331MT | Inductor 330uH ±20% 0A95 640mR Moulded SMD 12.5x12.5x8.0mm | L1, L2 | 2 | C169381 |
| MICRO 4P DIP | Micro USB Connector SMT with TH Mounts | P1 | 1 | C456008 |
| A2541WV-2x5P | Pin Header 10 Way Double Row Vertical Angle | P2, P3 | 2 | C225520 |
| A2541HWR-2x2P | Pin Header 4 Way Double Row Female Right Angle | P4, P5 | 2 | |
| CZM5,08-4E | Screw Down Terminal 5 Way 5.08mm Pitch | P6 | 1 | |
| AO3401A | MOSFET Trench 4A0 30V 85mR ±12V P-Channel Enhancement AOS SOT-22-3L | Q1 | 1 | C15127 |
| LBSS84LT1G | Small Signal MOSFET, 130 mA, 50 V, P-Channel, Enhancement, LRC SOT-23-3 | Q2, Q4 | 2 | C8492 |
| SS8050 | BJT NPN 1A5 25V SOT-23-3 | Q3, Q5 | 2 | C2150 |
| Res 0R 0805 | Jumper 0805 | R1 | 1 | C17477 |
| 0603WAF3300T5E | Lead Free Thick Film Chip Resistor 0805 ±1% | R2, R11, R29 | 3 | C23138 |
| 0603WAF1002T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R3, R38 | 2 | C25804 |

| | | | | |
|---|---|---|---|---|
| 0603WAF1200T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R4, R8 | 2 | C22787 |
| 0603WAF2400T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R5, R23 | 2 | C23350 |
| Res 68K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R6 | 1 | C23231 |
| Res 33K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R7, R12, R24, R25 | 4 | C4216 |
| RK09K1130AU2 | 5K Potentiometer THT 9.8mm Diameter ±20% 20VDC | R9, R30 | 2 | C388855 |
| 1206W4F680LT5E | Lead Free Thick Film Chip Resistor 1206 ±1% | R10, R26 | 2 | C19108 |
| Res 12K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R13 | 1 | C22790 |
| 0603WAF2701T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R14, R31 | 2 | C13167 |
| 0603WAF2702T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R15, R16, R33, R34 | 4 | C22967 |
| Res 100K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R17, R27, R32 | 3 | C25803 |
| Res 10K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R18 | 1 | C25804 |
| 0603WAF5602T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R19, R36 | 2 | C23206 |
| 0603WAF5601T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R20, R21, R35, R37 | 4 | C23189 |
| 0603WAF8201T5E | Lead Free Thick Film Chip Resistor 0603 ±1% | R22, R39 | 2 | C25981 |
| Res 56K 0603 | Lead Free Thick Film Chip Resistor 0603 ±1% | R28 | 1 | C23206 |
| SS12D07L2B | Switch Toggle Slider THT Vertical 0A3 50V | S1 | 1 | C480342 |
| LM317LBDR2G | 100mA, 1V2 - 37V Adjustable Output, Positive Voltage Regulator | U1 | 1 | C274645 |
| MC34063ADR2G | 1A5 Step-Up, Step-Down, Inverting Switching Reulator | U2, U5 | 2 | C32078 |
| LMV321IDBVR | OP AMP, 1MHZ, 1V/uS, SOT-23-5, FULL REEL; Bandwidth:1MHz; No. of Amplifiers:1; Slew Rate:1V/ s; Supply Voltage Range:2.7V to 5.5V; Amplifier Case Style:SOT-23; No. of Pins:5; Operating Temperature Min:-40 C; Packaging:Tape & Reel ;RoHS Compliant: Yes | U3, U6 | 2 | C7972 |
| LM337LMX | 100mA, -1V2 to -37V Adjustable Negative Voltage Regulator | U4 | 1 | C7947 |

# Appendix E — E12 Voltage Divider Script

```
#!/usr/local/bin/python3


print("Voltage Divider Solver (E12 Series)")
#Input parameters
Vcc = input("Enter the input voltage:\n\t")
Vcc = float(Vcc)
Vout = input("Enter the output voltage:\n\t")
Vout = float(Vout)

#Notify of convention
print("R1 is the resistor connected to ground")

#E12 Values
E12 = [1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82]

#Ratio to solve
B = Vout/Vcc

#Matrix of all possible combinations
A=[[None for i in range(len(E12))]for j in range(len(E12))]

#Build all possible combinatons
for i in range(len(E12)):
    for j in range(len(E12)):
        R1 = E12[i]
        R2 = E12[j]
        #R1 is the resistor closest to ground
        A[i][j] = R1/(R1+R2)

#Comparison array
D = [[None for i in range(len(E12))]for j in range(len(E12))]
#Determine the difference between A and B
for i in range(len(E12)):
    for j in range(len(E12)):
```

```
        D[i][j] = abs(A[i][j] - B)


#Find the minimum difference
#No difference will be greater than 1
min = 1
for i in range(len(E12)):
    for j in range(len(E12)):
        if(D[i][j]<min):
            min = D[i][j]
            imin = i
            jmin = j


#print optimal values
print("Best value for R1: "+str(E12[imin]))
print("Best value for R2: "+str(E12[jmin]))
print("Real output voltage is: "+str(round(A[imin][jmin]*Vcc, 2))+"V")


input()
```

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