Application Report
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Reverse Current Protection Using MOSFET and Comparator to Minimize Power Dissipation

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ABSTRACT

This application note describes how to implement Reverse Current Protection (RCP) using a comparator and a N-Channel MOSFET. RCP is a crucial protection scheme in load sharing applications where a dip in one line can result in an influx of current in another. This document presents a discrete alternative solution to protect against reverse current for cost-constrained systems.

Contents

1 Introduction 1
2 Definition of Reverse Current 2
3 Comparator Based Reverse Current Protection 2
4 Simulation 4
5 Test Results 7
6 Appendix 8
7 References 10

List of Figures

1 Simplified Comparator Based N-Channel Reverse Current Protection 2
2 N-Channel Reverse Current With Charge Pump Schematic 3
3 Simulated Results, MOSFET shorted Drain-Source 5
4 Simulated Results, RCP circuit enabled 5
5 Simulated Results, Negative Current Threshold Region 6
6 Load Current Verification, Protection Circuit Disabled (MOSFET Shorted D-S) 7
7 Test Results With Circuit Enabled 7
8 Close-up of Negative Current Region and Thresholds 7
9 Close-up of Negative Current Threshold With Hysteresis added 7
10 Test Circuit 9
11 OPA544 Power Amplifier 9

1 Introduction

As modern industrial applications continue to incorporate more and more electronics into their systems they must also include more protection from various supply faults. Simple reverse voltage protection can be added using several schemes involving diodes & MOSFETS, but they do not protect against reverse *current* flow. Reverse current protection is important in distributed, redundant, or hot-swap power supply applications where the loads could potentially force current back into the main bus voltage.

2 Definition of Reverse Current

Reverse current is where the load attempts to force current back into the power supply source.

Such instances can occur when the power supply source is suddenly reduced or completely lost, and the load supply bypass capacitors or batteries attempt to force current back into the power source when first connected. Reverse current can also occur when the load tries to force voltage back into the main supply bus, such as back-EMF from an inductive circuit or a failed battery charging circuit.

3 Comparator Based Reverse Current Protection

To enable reverse current protection, a comparator is placed across the MOSFET to monitor the direction of the current, as shown in Figure 1.

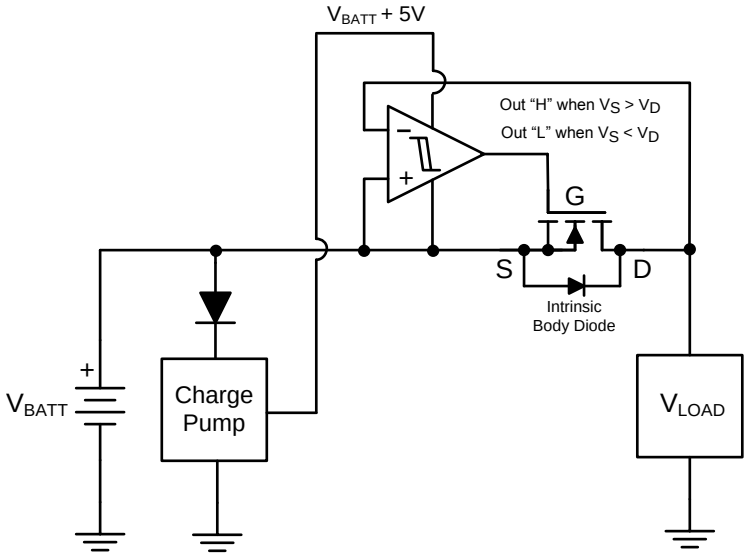


Figure 1. Simplified Comparator Based N-Channel Reverse Current Protection

Under normal positive current flow, a small voltage drop is created across the MOSFET $R_{DS(on)}$ due to the load current, which then creates a lower voltage on the Drain than on the Source. The comparator monitors this voltage difference.

If the current is reversed, the voltage on the Drain will be higher than on the Source. The comparator will detect this condition and set the output to low, turning the MOSFET off (not conducting) and isolating the load.

The sense voltage generated across the MOSFET is in the millivolts. A ground-referenced comparator would require elaborate level-shifting of the input signals to keep them within the comparators common mode range. The added level shifting circuitry would also increase the noise and drift of the small input signals.

To eliminate the losses and noise of level shifting, and also provide the needed peak current to directly drive the MOSFET into saturation, the comparators common is floated on the source supply voltage (V_{BATT}) so that the inputs, and output, can be directly connected to the MOSFET.

For the comparator circuit to function, it will need a supply voltage greater than the V_{BATT} voltage. The total comparator supply voltage must be chosen between the gate voltage required to ensure the lowest $R_{DS(on)}$, but stay safely below the $V_{GS(max)}$ of the MOSFET. For most MOSFETS, 5V is a good gate drive voltage.

To generate the comparator supply voltage for the comparator and MOSFET, a charge pump is used to create a voltage higher than the V_{BATT} voltage. The charge pump takes a square wave input signal and produces a DC voltage greater than the V_{BATT} voltage. Because the input to the charge pump is a capacitor, it is AC coupled, allowing the use of a ground-based square wave oscillator source.

3.1 Reverse Current Circuit Detailed Description

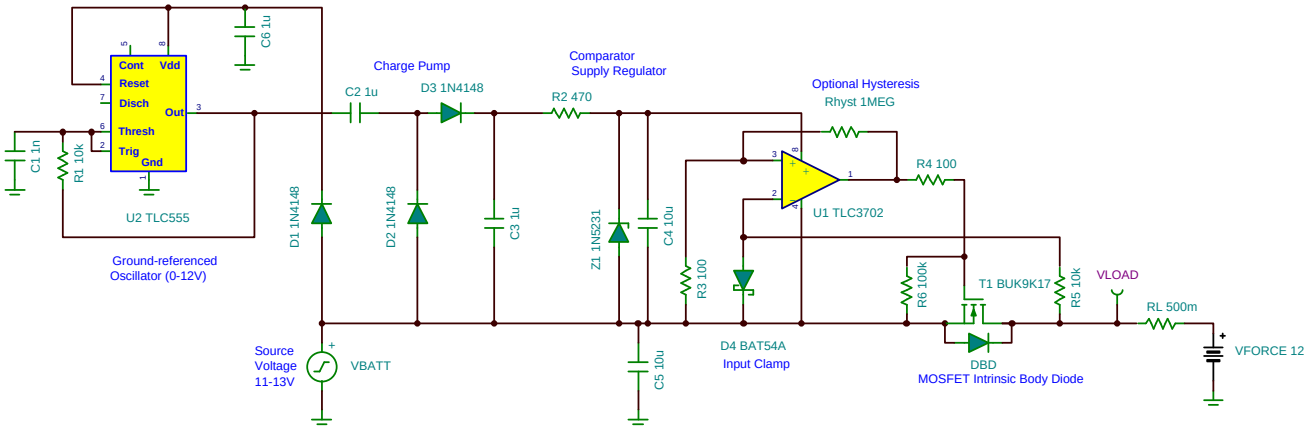


Figure 2. N-Channel Reverse Current With Charge Pump Schematic

Figure Figure 2 shows the full circuit.

The comparator is placed around the MOSFET to monitor the V_{DS} voltage.

To minimize effects due to noise or transients on the V_{BATT} line, the comparator circuit is "floated" on the V_{BATT} line. This eliminates issues With common mode rejection and the need for speed-reducing and signal attenuating level-shifting circuits.

The charge pump oscillator is a conventional LMC555 type multivibrator providing a 100kHz, 50% duty cycle square wave to drive the charge pump circuit through C2. D1 blocks reverse voltage and prevents the oscillator from running if V_{BATT} is a negative voltage.

The input to the charge pump circuit is AC coupled from a ground-referenced oscillator providing a peak-to-peak square wave equal to the amplitude of V_{BATT}. The AC source can be from a simple logic gate oscillator, 555 type oscillator, or the tapped output of an switching regulator or similar square wave source. The source must be capable of at least 20mA of peak current at 50% duty cycle for maximum efficiency.

Because the charge pump common is referenced at V_{BATT}, it will take up half of the "double", so the overall amplitude of the output of the charge pump output as seen by the comparator circuitry will be slightly less than the source voltage (due to conversion losses in the diodes). For a 12Vp-p AC source supply, the voltage seen across the comparator circuitry is about 10V due to losses in the diodes and driver output.

The Zener Z1 and series resistor R2 in the comparator circuit regulates the charge pump voltage down to a safe level for the comparator and the gate drive. This also regulates any anomalies due to transients or noise on the source supply.

Diodes D4A, D4B and resistor R5 network on the negative input clamps the voltage on the inverting input to ±300mV around V_{BATT}. Clamping is needed for the periods when the negative sense lead is pulled below the V_{BATT} line, such as when the MOSFET is first in body-diode conduction mode at power-up. The network also protects the negative input if V_{LOAD} greatly exceeds V_{BATT} due to load errors.

R6 is a pull-down resistor to insure the Gate is pulled to the source (not floating) when the comparator is unpowered.

R3 and R_{HYST} provide optional hysteresis should noise or oscillations occur at low or no load conditions. The choice of hysteresis value is a compromise between avoiding oscillations and minimum reverse current detection level. There is a tradeoff between the lowest negative current trip point and added hysteresis. For more information on hysteresis, see the Section 7 section at the end of this document.

The bypass capacitor C5 is essential because the charge pump requires a low impedance AC path to ground to function properly. Without C5, the charge pump peak currents can flow through the MOSFET sensing section causing false triggers, especially when the MOSFET is in body diode or reverse protect mode.

3.2 Component Selection

3.2.1 MOSFET

The on resistance $R_{DS(on)}$ of the MOSFET will have the greatest effect on circuit performance. The lower the $R_{DS(on)}$ of the MOSFET, the greater the reverse current required to trigger the protection. This is because the lower $R_{DS(on)}$ will drop less voltage across the MOSFET, so more negative current will be required to trigger the circuit.

It must be noted that the $R_{DS(on)}$ of the MOSFET has a positive temperature coefficient, where the $R_{DS(on)}$ increases with temperature. As a consequence, the reverse current threshold will decrease as temperature increases, and will increase at cold. So the maximum negative current limit must be tested at cold.

For example, a MOSFET with a $R_{DS(on)}$ of 20mΩ, a 1A reverse current will generate 20mV between the Drain and Source terminals. This $V_{GS(ON)}$ voltage will be referred to as the "sense" voltage.

For this design, the BUK9K17-60 from Nexperia was chosen for the low $R_{DS(ON)}$ resistance of about 20mΩ at a V_{GS} voltage of less than 4V, 60V $V_{DS(MAX)}$, and a convenient SO-8 package for bread boarding.

3.2.2 Comparator

The offset voltage of the comparator is seen in series with the sense voltage, either aiding or opposing depending on polarity, and represents one of the largest variances in the threshold point. The small sense voltage must now overcome the offset voltage to reach the threshold. The offset voltage specification in comparator datasheets is a plus/minus number (±1mV), so a positive and negative offset number calculations must be used in error budgets.

Due to the large capacitance of MOSFET Gates, typically around 1nF, a push-pull output comparator is desired to avoid the R-C time constant created by the gate capacitance and the pull-up resistor. To provide the fastest response, the comparator must turn off the MOSFET gate as quickly as possible. High output sinking-sourcing currents allow turning the Gate on and off faster.

Suitable devices are the TLC3701, TLV3201, TLV7011, LMV761 and LMV7239 comparator families.

3.2.3 Other Components

The selection of R2, the regulator series resistor, is a compromise on start-up time. From a "cold start" power-on, the comparator bulk bypass capacitor (C4) is charged through R2. The larger the value of C4, the longer the start-up time for the circuit (during which, the MOSFET will be in body-diode forward conduction mode). Conversely, a larger C4 will allow more "hold-up time" should the V_{BATT} voltage be interrupted or reduced during transients, providing protection during this time.

4 Simulation

The following are the results of the TINA-TI simulation of the circuit.

To verify the full current operation of the source circuit, the MOSFET Drain and Source will be shorted together to disable the protection.

Figure 3 shows the simulated result of the test circuit With the MOSFET shorted Source to Drain to verify the load current is flowing both positive and negative. the I_{LOAD} waveform shows the current flowing both +2A and -2A, crossing through zero. This verifies the operation of the driving circuitry. $V_{COMPOUT}$ stays high because there is no voltage change across the MOSFET due to the short.

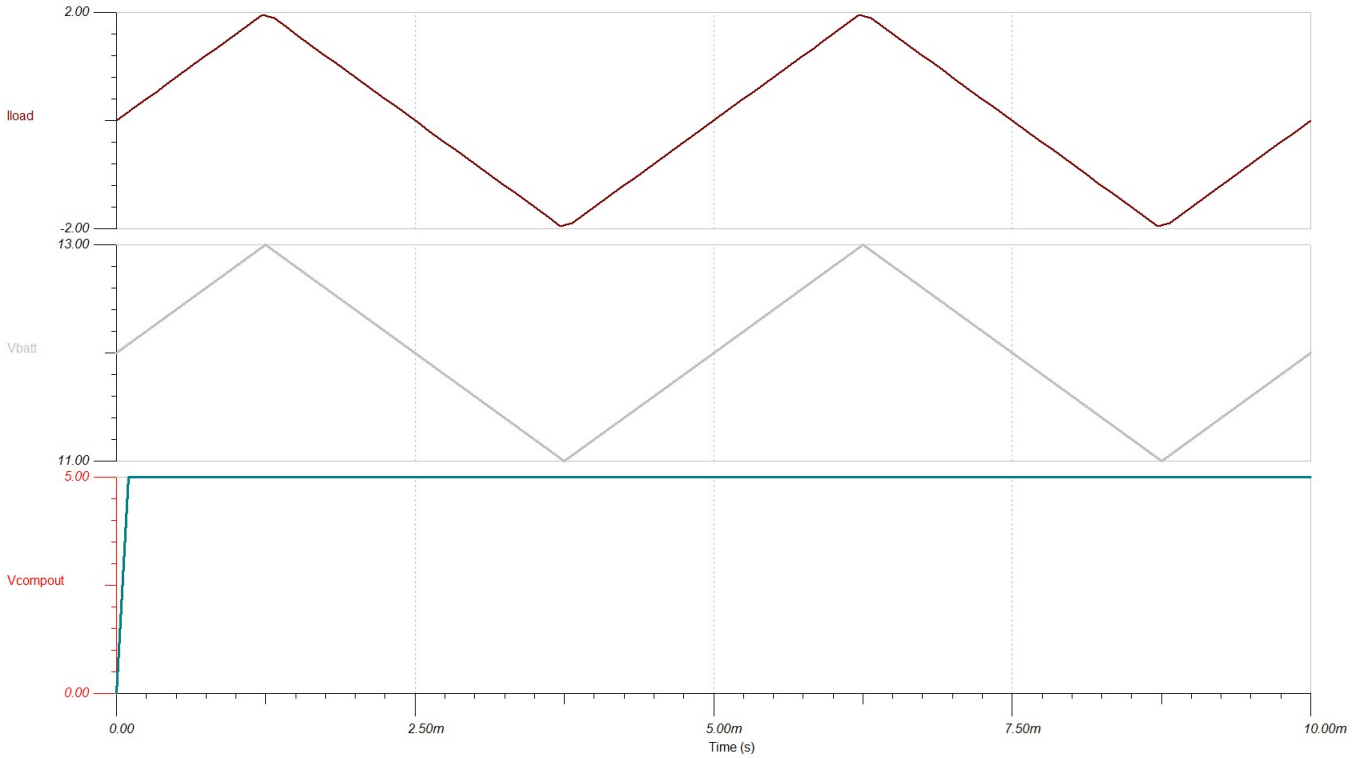


Figure 3. Simulated Results, MOSFET shorted Drain-Source

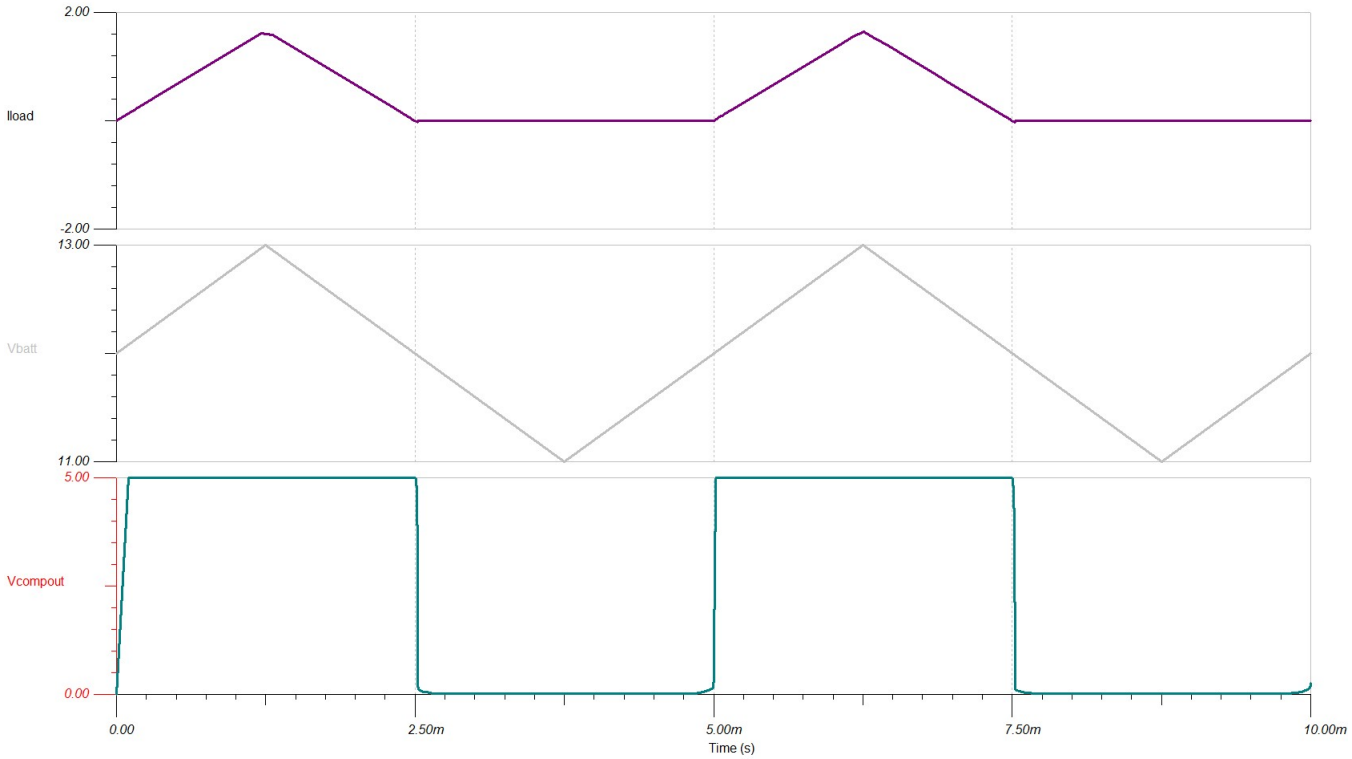


Figure 4. Simulated Results, RCP circuit enabled

Figure 4 shows the simulated result of the test circuit with the Drain to Source short removed.

As can be seen in Figure 4, as I_{LOAD} crosses zero current and heads negative , the comparator output (Vcompout) goes low and turns off the MOSFET, isolating the load and reducing the load current to zero.

Figure 5 shows a close-up view of the negative portion of the current waveform and the comparator output state. This shows where the negative current trip-point occurs.

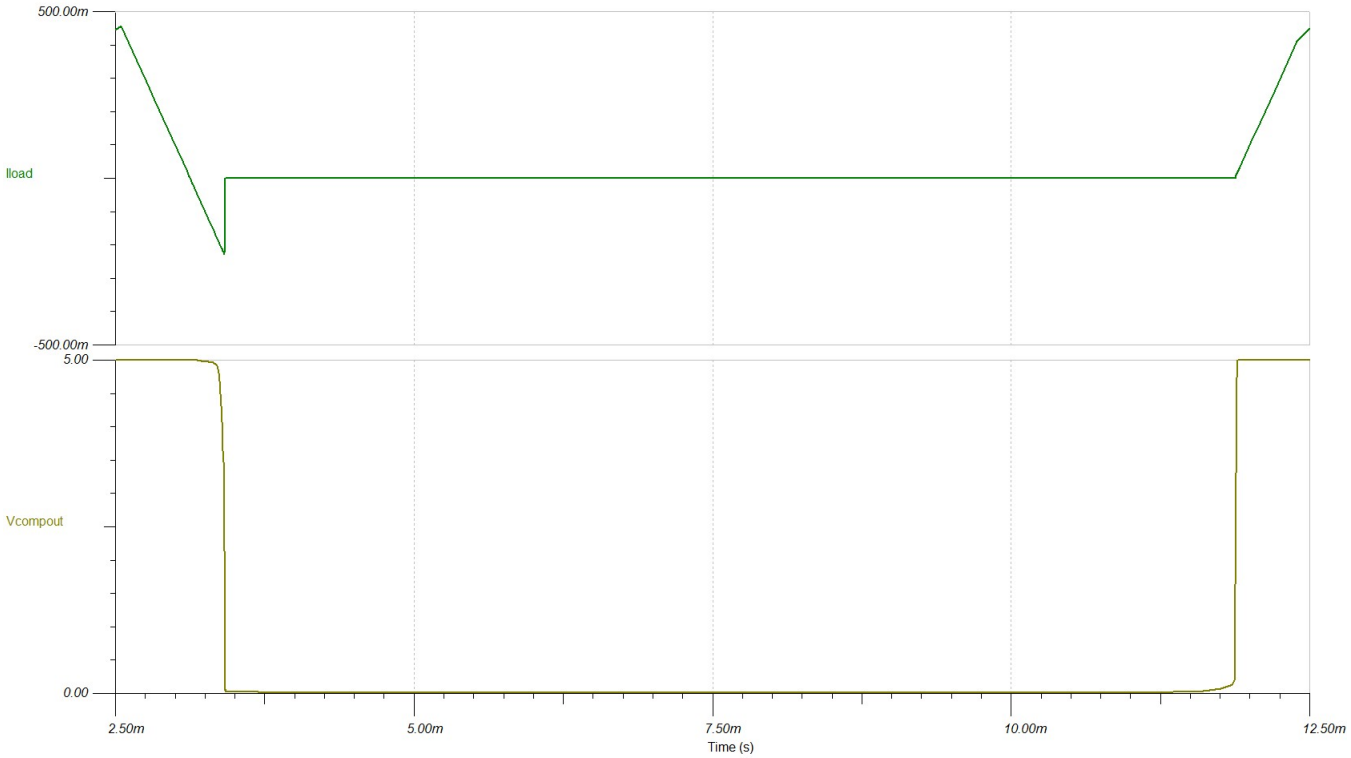


Figure 5. Simulated Results, Negative Current Threshold Region

Detection of the negative current takes longer (as indicated by the "undershoot" in the current waveform in Figure 5) due to the fact the MOSFET is conducting with low resistance at this time, which reduces the voltage dropped across the MOSFET, as opposed to the larger 0.8V forward drop of the body diode when the MOSFET is not conducting. If the negative current "overshoot" is unacceptable, it may be necessary to add some series resistence to increase the voltage drop across the MOSFET stage.

The reaction time to the reverse current is dependent on four parameters:

1. The $R_{DS(on)}$ of the MOSFET
2. The offset voltage of the comparator
3. The propagation delay of the comparator
4. The current waveform rise/fall time
5. Applied hysteresis

Numbers 1, 2 and 5 will have the greatest effect at DC and slow transition speeds. The $R_{DS(on)}$ of the MOSFET will have the widest variation due to device-to-device differences and load conditions.

Numbers 3 and 4 will determine the minimum trigger current on current transients that have edge rates close to the response time of the comparator. Because the comparator response time is fixed, the peak reverse current will increase as the speed of the current waveform edge increases. It is possible to use a faster comparator, but the speed of the comparators output may be limited due to delays driving the MOSFET into saturation due to the large MOSFET input capacitance.

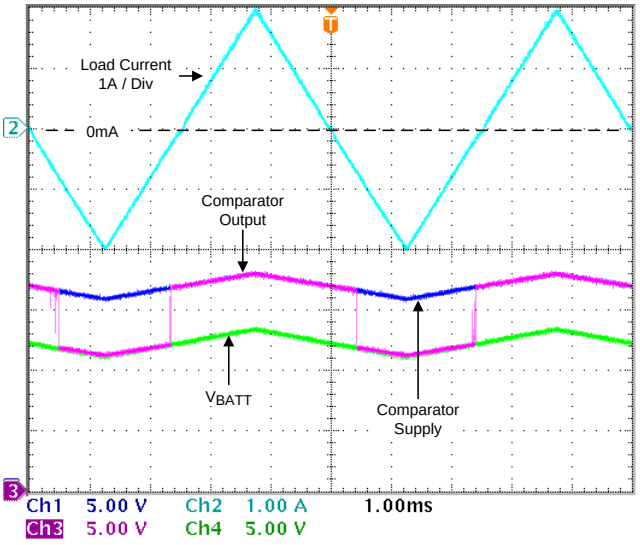
Hysteresis can be added to minimize "chatter" as the current approaches the threshold. Number 5 will have the greatest effect on the trip point.

5 Test Results

The actual circuit was tested by applying a 200Hz, +11 to +13V triangle wave to V_{BATT} , and a fixed 12V for V_{LOAD}. The load resistor is 0.5Ω. This creates a ±2A current through the load resistor. The setup used to generate the currents is described in the Section 6.

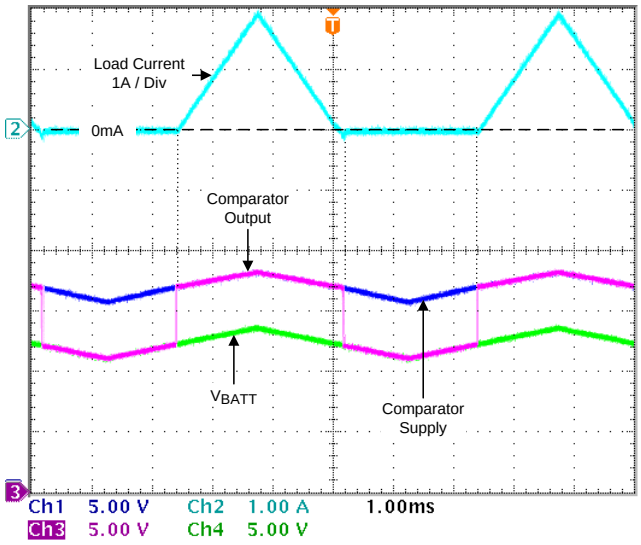
5.1 Load Current Verification

To verify the load current is correct, the reverse current circuit protection was disabled by shorting the MOSFET Drain to Source to allow both positive and negative currents. The resulting waveforms are shown in Figure 6.



Ch4 is Comparator Supply Voltage, 5V/Div

Figure 6. Load Current Verification, Protection Circuit Disabled (MOSFET Shorted D-S)



Ch4 is the V_{BATT} voltage, 5V/Div

Figure 7. Test Results With Circuit Enabled

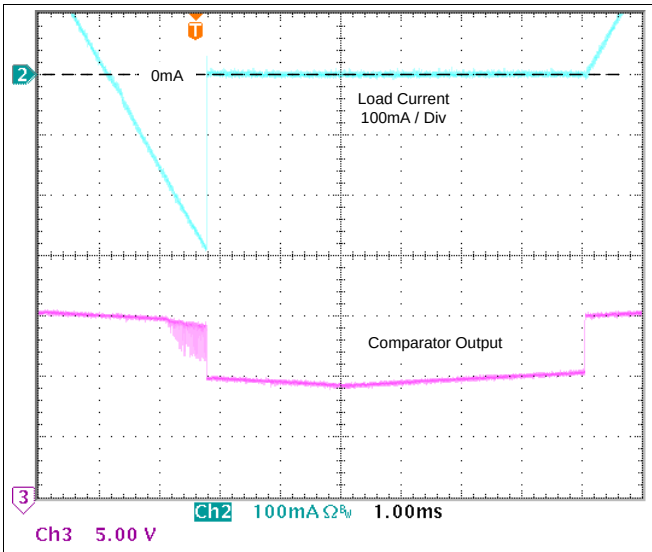
Figure 6 The top light blue load current waveform clearly shows the load current flowing to -2A, through zero, and up to +2A.

The green trace is the V_{BATT} voltage, moving between 11V and 13V. The dark blue trace is the comparator supply voltage provided by the charge pump, which is regulated 5V above V_{BATT}. The cyan waveform is the output of the comparator driving the MOSFET gate, which will swing between V_{BATT} and the comparator supply voltage. Note the comparator output goes "low" when the output current goes negative, and goes high when the current goes positive.

5.2 Circuit Operating

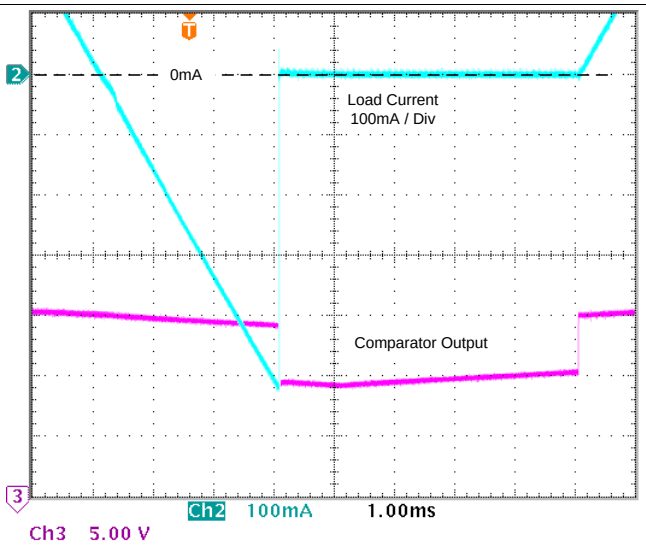
The Drain-Source short was removed and the proper operation of the Reverse Current Protection circuit can now be observed in Figure 8

As can be seen in Figure 7, the negative portion of the top light blue current waveform is clipped during the negative portion. The comparator output goes low when the load current passes down through zero, then goes high when the current rises up from zero. There is a slight "undershoot" when the current passes through the negative portion, which is expanded in Figure 7 .



Ch3 (bottom) is the Comparator Output at 5V/Div

Figure 8. Close-up of Negative Current Region and Thresholds



Ch3 (bottom) is the Comparator Output at 5V/Div

Figure 9. Close-up of Negative Current Threshold With Hysteresis added

Figure 7 shows a close-up of the negative current "undershoot" region and the comparator output state. The comparator output starts "chattering" when the negative current approaches -150mA, and fully triggers at -300mA. The MOSFET remains off while the current is negative because the comparator output is low (V_{GS} = 0V).

The "chattering" seen in Figure 7 is common in comparator applications when the input signal is near zero and on the verge of transition, and the comparator triggers on noise. The next section Section 5.3 will discuss how to minimize the "chatter".

As the current heads positive and crosses through zero, as seen in the last division of Figure 7, the comparator output goes high to turn the MOSFET back on to re-connect the load. Because the voltage across the MOSFET is largest when the MOSFET is not conducting, due to the approximately 700mV across the forward biased body diode, the positive turn-on will occur faster and at a more consistent level.

As mentioned in the previous circuit description, the amount of the reverse current "undershoot" depends on the combination of the $R_{DS(ON)}$ of the MOSFET, the offset voltage of the comparator, and any added hysteresis.

5.3 Applying Hysteresis

To reduce this "chattering", hysteresis can be added to the circuit. However, adding hysteresis will decrease the sensitivity and increase the negative current trip point due to the raising of the trip-point threshold.

Figure 9 demonstrates the difference of adding a 1MΩ hysteresis resistor to reduce the "chattering". As a result. the negative trip pont has moved to almost -500mA due to the higher input voltage required to overcome the added hysteresis threshold.

6 Appendix

6.1 Test Circuit

To test the reverse current circuit, it is necessary to create positive and negative currents with fast, controllable edges and slopes. This is difficult to accomplish at high currents.

The basic concept is that a load resistor is placed in series between two individually controllable voltage sources.

When both sources are at equal voltage, the voltage across the load resistor R_L is zero and no current is flowing.

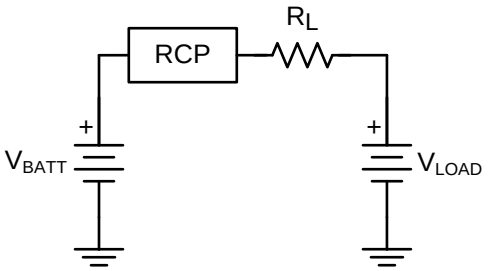


Figure 10. Test Circuit

Assuming a 1Ω load resistor for R_L, if the V_{BATT} supply is raised 1V above V_{LOAD}, then there will be 1V across the load resistor, creating a +1A current flow (current flowing into the load).

If the V_{BATT} supply is lowered 1V, then -1V will be across the load resistor, creating a -1A current flow (current flowing out of the load).

Typical bench supplies cannot be used because they cannot sink current. The simple series-pass architecture of common bench supplies cannot "pull-down" the supply output to prevent the output from being pulled above the regulated set point. This will cause problems with this test circuit because the circuit is actually forcing the output of one supply into another supply through the load resistor, so the higher voltage of the two will dominate and current will not flow.

For proper functionality, both supplies will need to be able to sink and source current ("four-quadrant" operation), as well as be able to generate ramps and transitions.

There are "four quadrant" power supplies commercially available, however they tend to be costly, too slow or difficult to control. Instead, an external power amplifier is used for the voltage sources. The amplifier is essentially a DC coupled audio power amplifier, which is able to both sink and source current, when driven by a function generator.

6.2 Power Amplifier Description

The OPA544 2A power operational amplifier was used for the power supply sources. A closed loop gain of 10 was used as a compromise between required bandwidth, stability and gain needed for the function generator maximum output swing. An arbitrary waveform generator was used as the input source to the amplifier to produce the test waveforms.

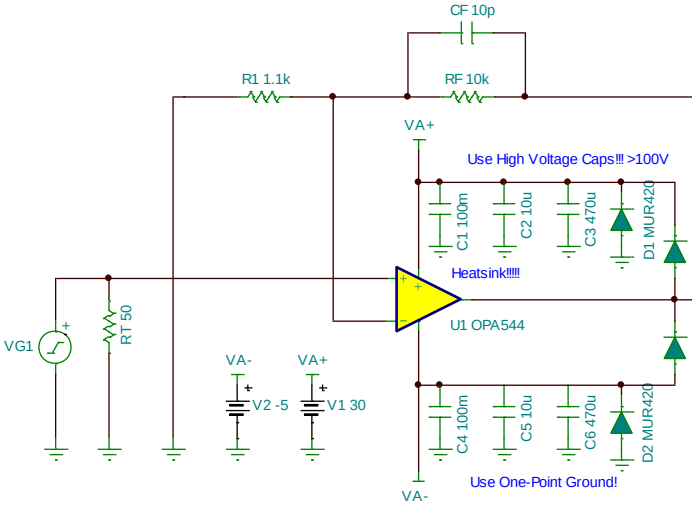


Figure 11. OPA544 Power Amplifier

Asymmetrical supplies provided by an adjustable bench supply are used to accommodate the larger positive output swing. A minimum of 5V headroom is needed on either supply to maintain proper operation. To achieve the desired 0V to 20V output swing, asymmetrical supplies of -5V and +25V were used. Generous heatsinking of the amplifier is required due to the required power dissipation associated with continuous DC output current. Power dissipation is kept low by adjusting the total supply voltage just above the required peak voltage (V_{PEAK} + 5V). The power supplies must also have adjustable current limit, set a little above the required peak current, to limit the current to prevent damage to the amplifiers if there is a mishap or short.

The resulting amplifier bandwidth exceeded 30kHz and met the 20V @ 2A drive requirement.

7 References

- "Reverse Current Protection in Load Switches", Texas Instruments Application Note, Literature Number SLVA730
- "Comparator With and Without Hysteresis", Texas Instruments Application Note, Literature Number SBOA219
- "Comparator with Hysteresis Reference Design", Texas Instruments Reference Design, Literature Number TIPD144
- "TLC555-Q1 Used as a Positive and Negative Charge Pump", Texas Instruments Application Note, Literature Number SLFA002
- "BUK9K17-60E N-Channel MOSFET datasheet", Nexperia Corporation

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