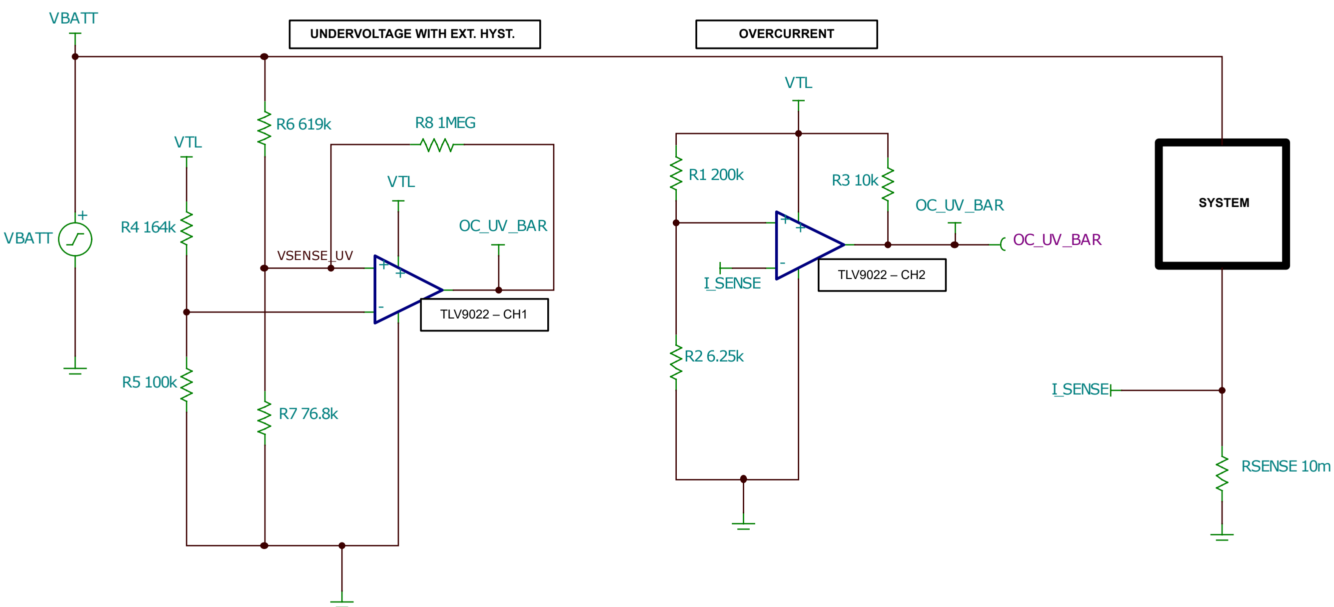
Analog Engineer's Circuit Amplifiers

How To Protect 48-V Batteries from Overcurrent and Undervoltage

Introduction

As E-Bikes and other battery assisted vehicles are becoming increasingly popular in major cities, it is important to maintain electrical safety when designing with high-voltage, lithium-ion batteries. To safely operate such a battery, the discharge current rate and battery voltage level must be monitored. Undervoltage protection is crucial when using lithium-ion batteries because if the battery is discharged below its rated value, the battery will become damaged and potentially pose a safety hazard. In addition to undervoltage protection, it is important to ensure that the battery is discharging a safe current value. Combining undervoltage protection and overcurrent protection will ensure safe operation of the 48-V battery.

Design Process



For this design, a 48-V, 20-Ah lithium-ion battery was selected. Monitoring a 48-V lithium ion battery can be achieved using the TLV9022 device in combination with the TL431 shunt reference. The TLV9022 is a dual-channel, open-drain comparator that will be used to implement overcurrent and undervoltage protection. This comparator was selected for its low-input offset voltage and fast response time. Additionally, this comparator has fault-tolerant inputs that can go up to 6V without damage. The design process will be broken down into three main sections: Voltage Regulation, Overcurrent Protection, and Undervoltage Protection with Hysteresis. This design has design parameters and desired outputs shown in the following table.

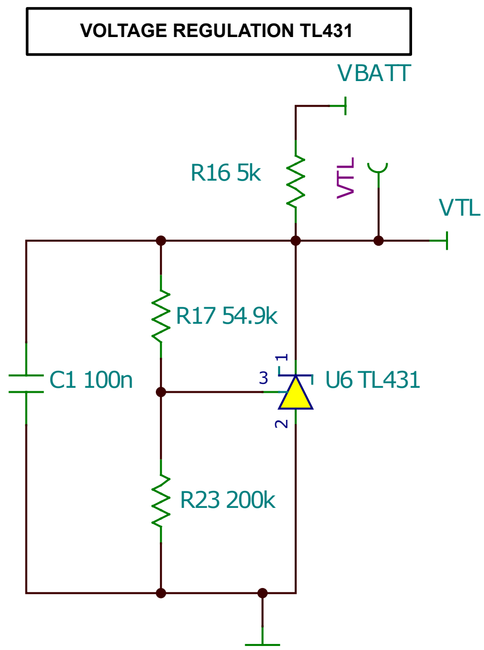
Design Parameters and Desired Outputs [1] [2]

System Supply	Undervoltage Limit	Undervoltage Reset	Overcurrent Limit	Comparator Output Status		
Typical	V_{UV}	V_{RES}	I_{OC}	Overcurrent	Undervoltage	Normal Operation
29 V	10 V	12 V	10 A	CH1-HIGH	CH1-LOW	CH1-HIGH
				CH2-LOW	CH2-HIGH	CH2-HIGH

1. The design parameters and desired outputs table assumes a typical value of 29-V for the 48-V battery as it is the midpoint between the maximum voltage value and the undervoltage limit.
2. The design parameters and desired outputs table assumes only one condition (OC or UV) is met at a time at a time.

Voltage Regulation

Since the intended use of the comparator outputs is to input them into a microcontroller, the desired reference voltage is approximately 3.3-V. The image below illustrates the circuit configuration for the TL431 device. Using the standard 1% resistor values shown, the voltage seen at the output of the TLV431 is 3.29-V. For the design process, see the *TL431 / TL432 Precision Programmable Reference Data Sheet*.



TL431 3.29-V Reference

Undervoltage Protection With Hysteresis

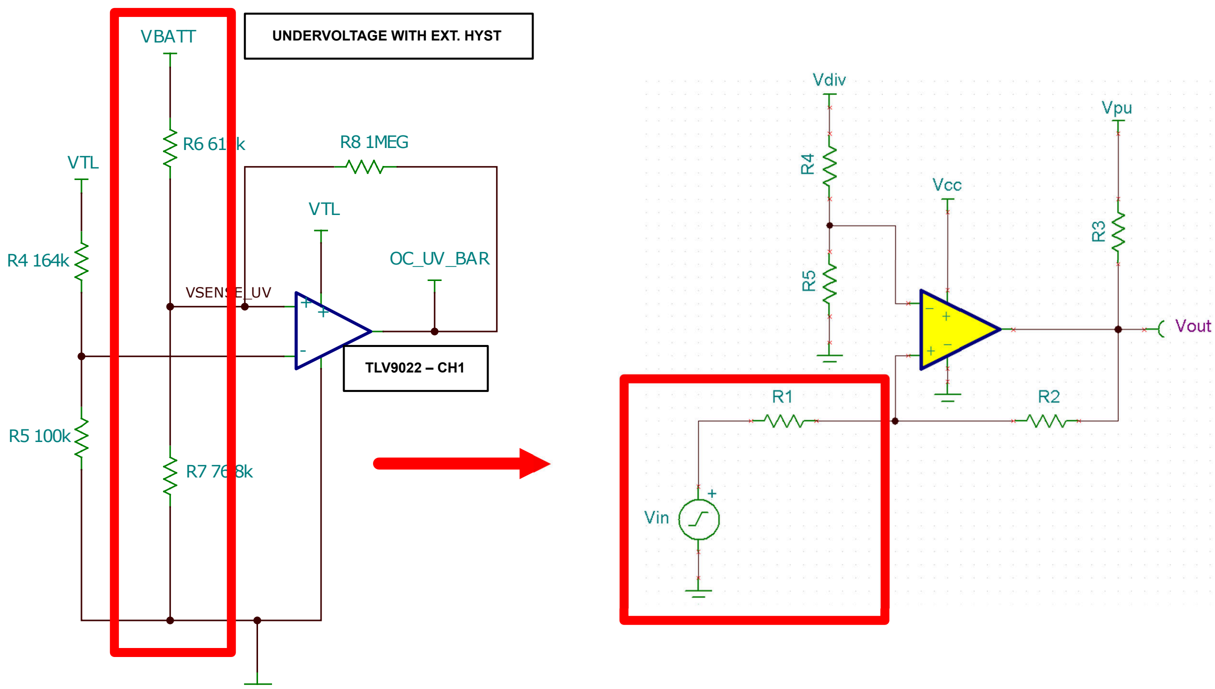
The undervoltage condition for this design is when the battery voltage, VBATT, is 10-V. The voltage seen at the pin of the comparator must not exceed 5.7-V as specified in the *Recommended Operating Condition* table of the *TLV902x and TLV903x High-Precision Dual and Quad Comparators Data Sheet*.

To determine how much the battery voltage should be reduced to stay below the 5.7-V input voltage limit, consider the maximum battery voltage of 48-V. At this value, the voltage must be divided down by a factor of 8.42. For this example, we round up to 9 to be safe.

This means that the following equation must be true to yield a maximum non-inverting input voltage of approximately 5.33-V.

$$\frac{R_7}{R_6 + R_7} \equiv \frac{1}{9}$$

Next, use the external hysteresis tool posted on this E2E thread. This excel tool is based on the *Inverting Comparator with Hysteresis Circuit* and Non-inverting comparator with hysteresis circuit amplifier cookbooks. Due to the configuration of the tool, we need to create a Thevenin Equivalent source and resistance for VBATT, R6, and R7 to match Vin and R1 in the hysteresis tool circuit on the right side of the image below.



Format Conversion of Design Circuit to Use Excel Tool

Therefore, the equivalent R1 for the tool is the parallel combination of R6 and R7. R8 is equal to the R2 output value, R3 is the selected 10-kΩ pullup, and R4 and R5 are consistent for the tool and the design. The Thevenin equivalent undervoltage value would be the undervoltage threshold value divided by 9. This would be approximately 1.11-V for the 10-V undervoltage value. In this design, we have a desired undervoltage reset (V_{RES}) of 12-V when recovering from an undervoltage condition. This V_{RES} level of 12-V also has to be divided by 9, translating to a 1.333-V input into the tool. V_{CC}, V_{DIV}, and V_{PU} are all equal to the reference voltage established by the TL431 device of 3.29-V.

Voltages

Vcc (V)	Vdiv (V)	Vpu (V)	Vh (V)	Vl (V)	Vhyst_int (mV)
3.29	3.29	3.29	1.333	1.111	0

Modes

Output Stage	Resistor Range	Comparator Configuration
OD	MΩ	NON

INPUT

OUTPUT

Resistors

R1 (Ω)	R2 (Ω)	R3 (Ω)	R4 (Ω)	R5 (Ω)
67.89E+3	1.00E+6	10.00E+3	1.64E+6	1.00E+6

External Hysteresis Excel Tool Inputs and Outputs

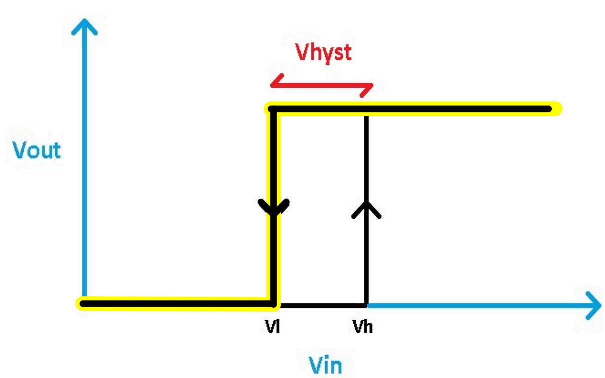
Using the values provided by the tool, we know that the parallel combination of R7 and R6 must equal R1. This means that the following equation must be true.

$$\frac{R_6 \times R_7}{R_6 + R_7} = 67.89\ k\,\Omega$$

Using the previous equation and the following equation, solve for the ideal values of R7 and R6.

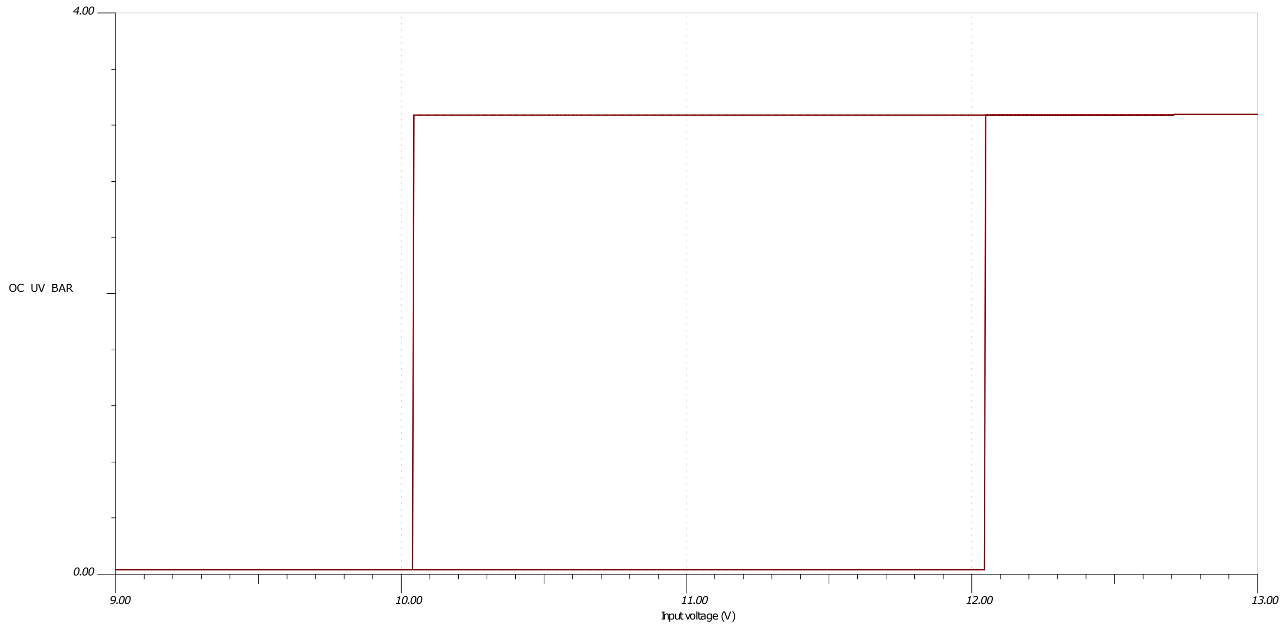
$$\frac{R_7}{R_6 + R_7} = \frac{1}{9}$$

For this design, the ideal values of R7 and R6 are 76.38kΩ and 611.01kΩ, respectively. For this design, the voltage will most likely be decreasing. This means that the section of the hysteresis transfer curve highlighted by the following figure is important when determining a standard resistor value for R6.



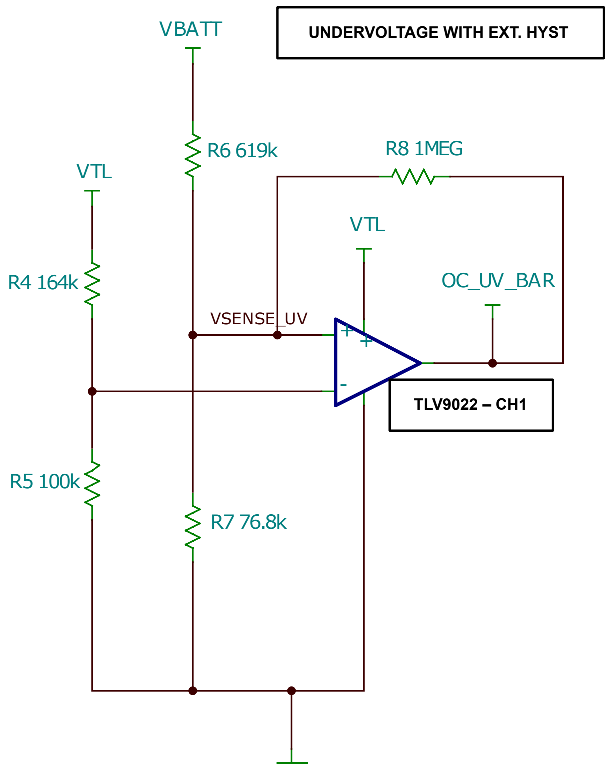
Hysteresis Transfer Curve With Highlighted High-to-Low Transition

If a standard resistor value less than 611.01kΩ is selected for R6, then the voltage seen at the non-inverting pin of the CH1 comparator will be slightly higher than desired. In other words, the voltage drop across R6 will be smaller as its resistance decreases. With a fixed, divided voltage seen at the non-inverting pin, it is important to select a resistance slightly larger than 611.01kΩ for R6. This would result in a high-to-low transition slightly before the desired 10-V value (further to the right on the x-axis in the previous figure). This is preferable because lithium-ion batteries must not be depleted below the rated voltage value. This is why a slightly higher than theoretical 1% standard resistor value of 619kΩ was selected for R6. See the impact of this resistor selection on the following voltage transfer curve.



Simulated Voltage Transfer Curve

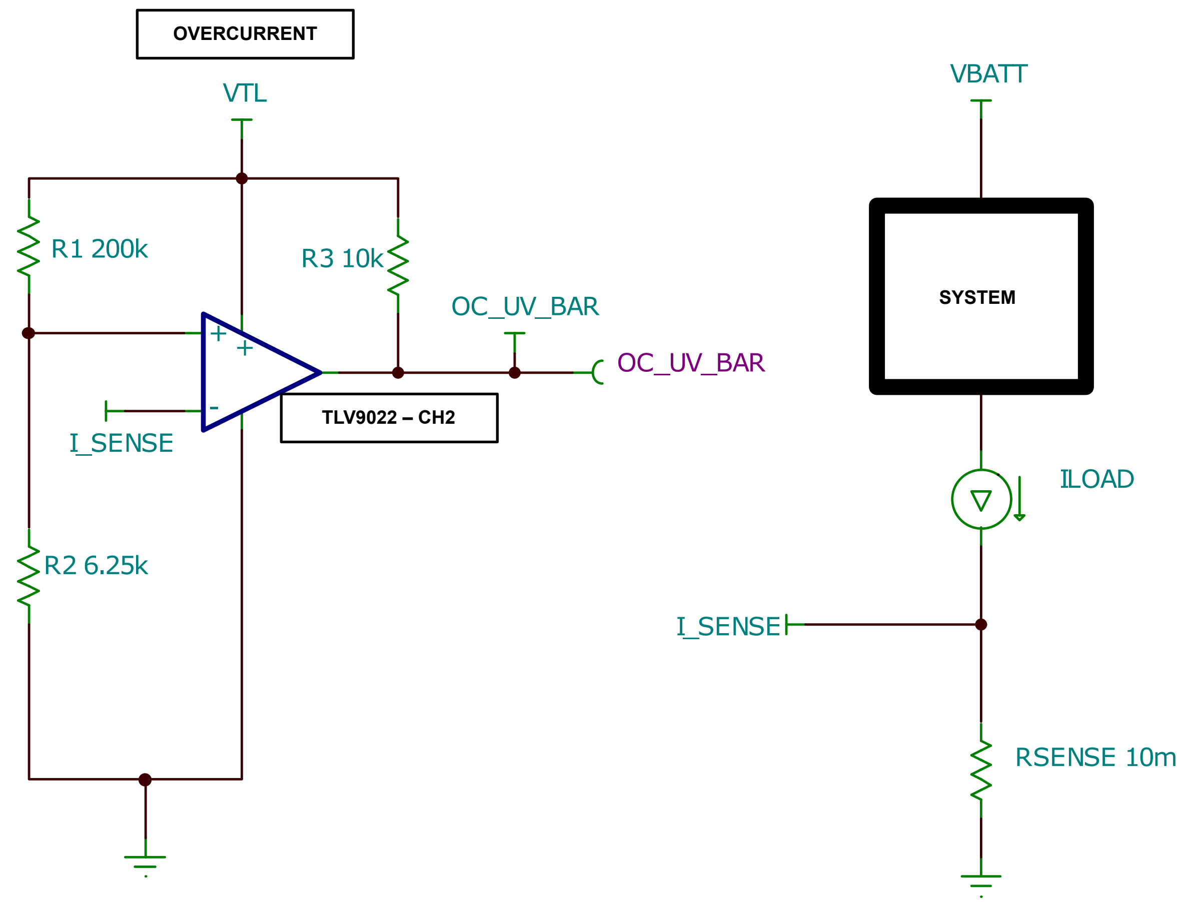
For this design, the standard 1% values of R7 and R6 are 76.8kΩ and 619kΩ, respectively.



Completed Undervoltage Protection Circuit With External Hysteresis

VTL must also be divided down to match the 1.111-V undervoltage threshold. Even though the tool provides values for R4 and R5, both of these resistances do not impact the positive feedback. This means the ratio of the two resistances is all that needs to be maintained. This is why we are able to select R4 and R5 to be 164kΩ and 100kΩ, respectively.

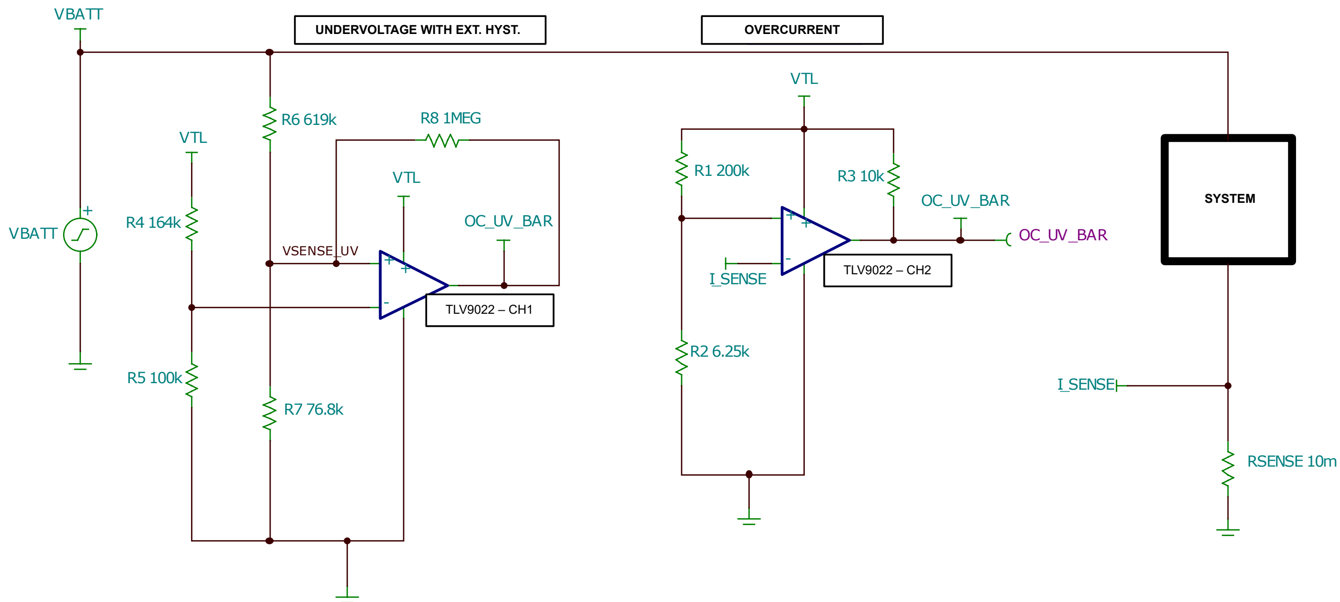
Overcurrent Protection



Completed Overcurrent Protection Circuit With Simulated Load Current

To determine an appropriate overcurrent value, it is recommended to set the limit to roughly half of the battery usage rating or use the maximum discharge current rating of the battery. For this design, we are assuming a usage rating of 20Ah. This means we selected an overcurrent threshold of 10A. This approximately translates to two hours of battery life if the maximum current rating is maintained. A 10-mΩ resistor is used to sense the load current. This means that when a voltage of approximately 100mV is seen by the first channel of the TLV9022, the combined output of the channels will be pulled low. Using the resistive network in the previous image, where R1 and R2 are equal to 200kΩ and 6.25kΩ, respectively, will step the VTL voltage down from 3.29-V to approximately 100mV. This establishes the overcurrent threshold at 10A.

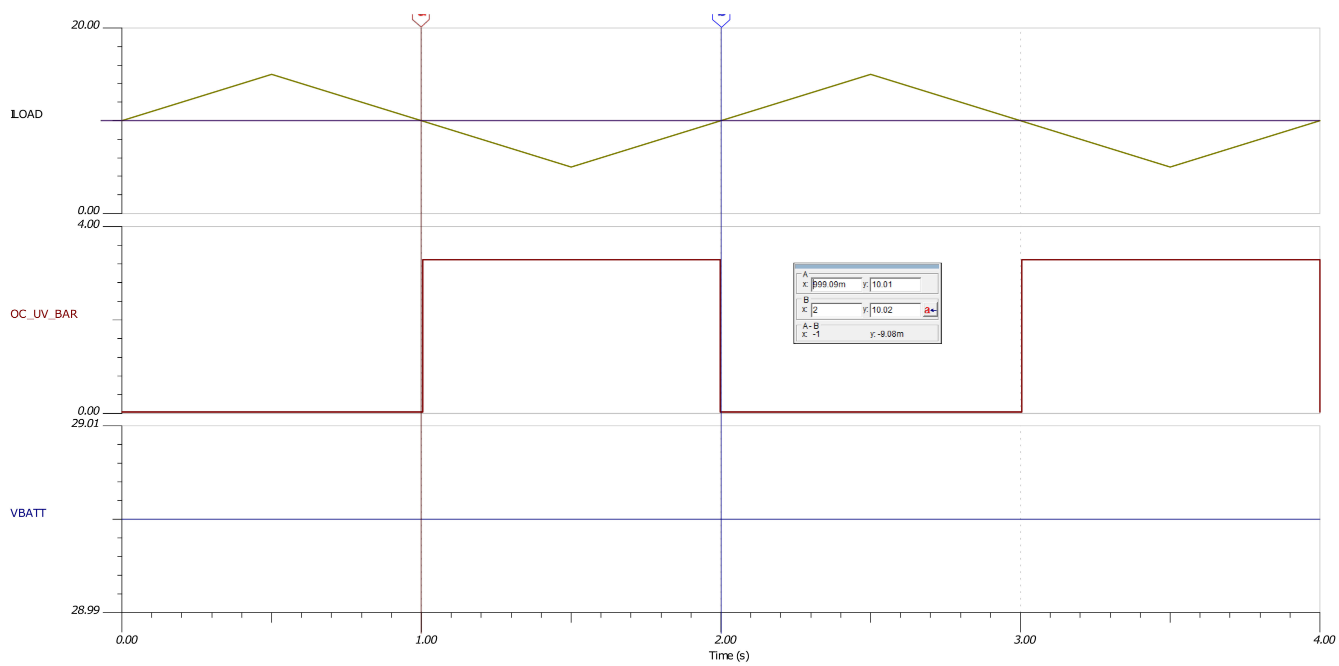
Final Considerations



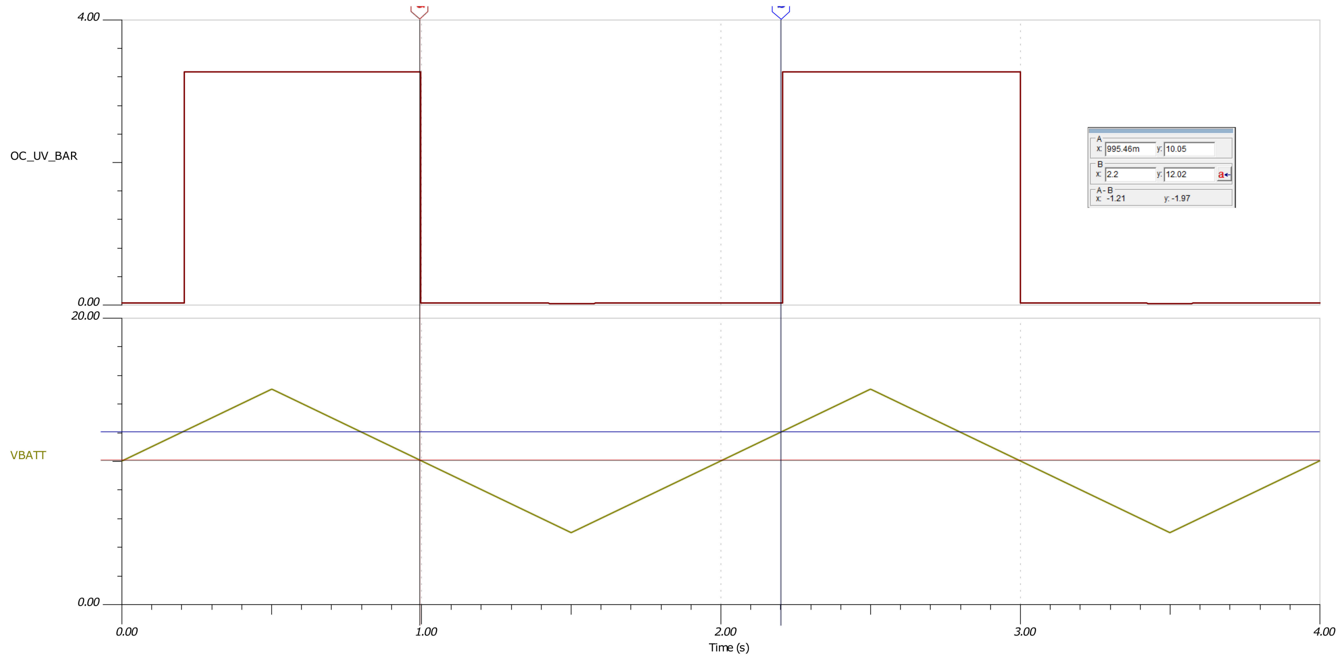
Completed Protection Circuit

If there is a need for window comparators for the voltage and current values, then two channels may be added to this design. Both of the channel outputs are combined by shorting both open-drain outputs together in what is referred to as AND configuration (when either outputs a logic low, the combined output is also low). To have distinct outputs, use a separate pullup resistor for the first channel of the TLV9022. Low-side current sensing with a 10-mΩ sense resistor was used to achieve overcurrent protection at 10A. If a smaller resistance or lower current threshold is needed, you can use an even smaller resistance in combination with an amplifier.

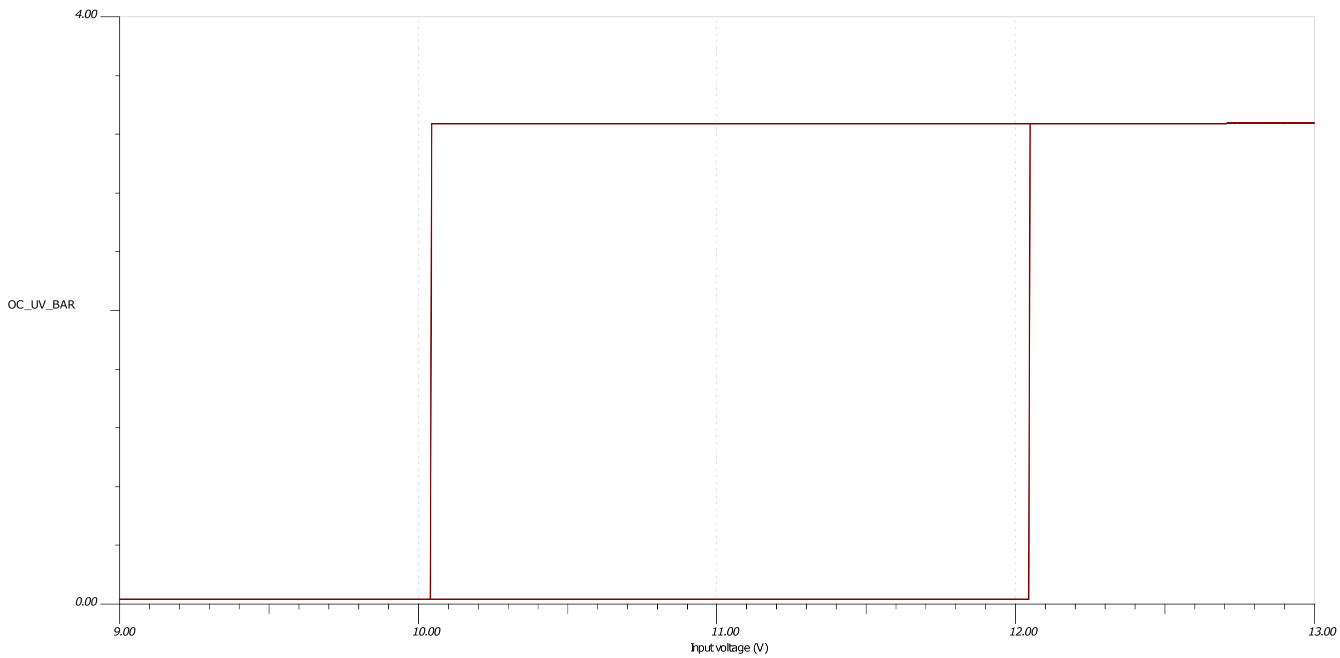
Simulation Results



Overcurrent Test: Current Generator Through Load Spanning From 15A to 5A, at Typical Battery Level



Undervoltage Test: Voltage Generator Across Load Spanning from 15-V to 5-V



Undervoltage Test: Voltage Transfer Curve

Design References

See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.

See the *Non-inverting comparator with hysteresis circuit*.

Circuit SPICE Simulation File: SNOM707

For more information on many comparator topics including hysteresis, propagation delay, and input common-mode range, see training.ti.com/ti-precision-labs-op-amps.

Design Featured Comparator

TLV9022	
V_s	1.65V–5.5V
V_{inCM}	–0.2V to 5.7V
V_{os} (offset voltage @ 25 C) (Max) (mV)	1.5
I_q	15µA per channel
T_{PD} (us)	0.15
Output type	Open-drain
#Channels	2
www.ti.com/product/tlv9022	

Design Alternate Comparator

TLV7022	
V_s	1.6V to 6.5V
V_{inCM}	V_{CC} - 0.1V to V_{EE} + 0.2V
V_{os} (offset voltage @ 25 C) (Max) (mV)	8
I_q per channel (Typ) (mA)	0.0047
T_{PD} (us)	0.26
Output Type	Open-drain
#Channels	2
www.ti.com/product/tlv7022	

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