

Current Sense Circuit Collection

Making Sense of Current

Tim Regan, Editor

INTRODUCTION

Sensing and/or controlling current flow is a fundamental requirement in many electronics systems, and the techniques to do so are as diverse as the applications themselves. This Application Note compiles solutions to current sensing problems and organizes the solutions by general application type. These circuits have been culled from a variety of Linear Technology documents.

Circuits Organized by General Application

Each chapter collects together applications that tend to solve a similar general problem, such as high side current sensing, or negative supply sensing. The chapters are titled accordingly (see “Circuit Collection Index” below). In this way, the reader has access to many possible solutions to a particular problem in one place.

It is unlikely that any particular circuit shown will exactly meet the requirements for a specific design, but the suggestion of many circuit techniques and devices should prove useful. Specific circuits may appear in several chapters if they have broad application.

This Application Note Will Change


This Application Note is a growing and changing document. Many of the chapters listed below are placeholders for material that will be filled in soon. As the chapters are added, their links will be enabled.

Using the Application Note

Click the name of a chapter in the “Circuit Collection Index” below to open the PDF version of that chapter.

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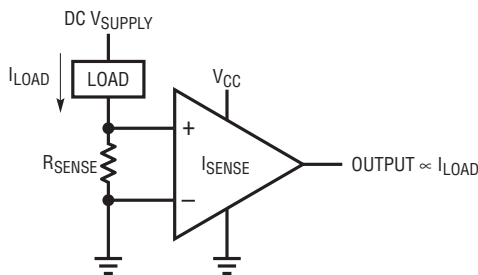
Current Sense Basics

This chapter introduces the basic techniques used for sensing current. It serves also as a definition of common terms. Each technique has advantages and disadvantages and these are described. The types of amplifiers used to implement the circuits are provided.

To see other chapters in this Application Note, return to the [Introduction](#).

LOW SIDE CURRENT SENSING

Current sensed in the ground return path of the power connection to the monitored load. Current generally flows in just one direction (uni-directional). Any switching is performed on the load-side of monitor.



Low Side Advantages

- Low input common mode voltage
- Ground referenced output voltage
- Easy single supply design

Low Side Disadvantages

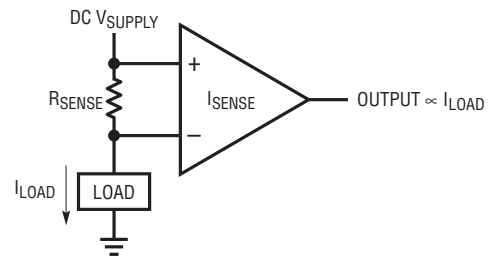
- Load lifted from direct ground connection
- Load activated by accidental short at ground end load switch
- High load current caused by short is not detected

Amplifier Types for Low Side Implementation

- Precision zero-drift op amps: LTC2050, LTC2054
- Instrumentation amplifiers: LTC2053, LT1990, LTC6943
- Rail-to-Rail Input op amps: LT1677

HIGH SIDE CURRENT SENSING

Current sensed in the supply path of the power connection to the monitored load. Current generally flows in just one direction (uni-directional). Any switching is performed on the load-side of monitor.



High Side Advantages

- Load is grounded
- Load not activated by accidental short at power connection
- High load current caused by short is detected

High Side Disadvantages

- High input common mode voltages (often very high)
- Output needs to be level shifted down to system operating voltage levels

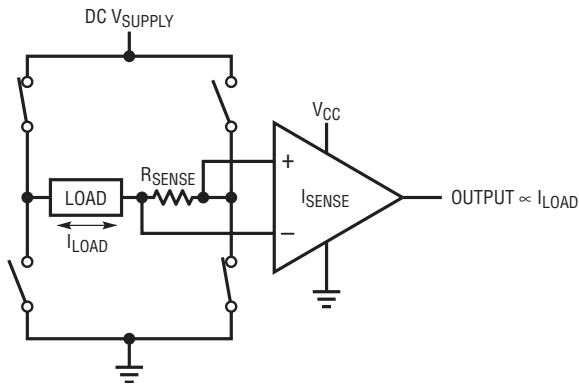
Amplifier Types for High Side Implementation

- Dedicated current sensing amplifiers: LT6100, LTC6101, LT1787
- Over-the-Top™ op amps: LT1637
- Flying capacitor amplifier: LTC6943

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FULL-RANGE (HIGH AND LOW SIDE) CURRENT SENSING

Bi-directional current sensed in a bridge driven load, or unidirectional high side connection with a supply side switch.



SUMMARY OF CURRENT SENSE SOLUTIONS

The next few pages contain a table that summarizes current sense solutions and applicable devices. Look first in the “Type/Circuit” column and the “Gain” column for a general description of the application. Then scan across the other columns for applicable devices and their specifications.

Full-Range Advantages

- Only one current sense resistor needed for bidirectional sensing
- Convenient sensing of load current on/off profiles for inductive loads

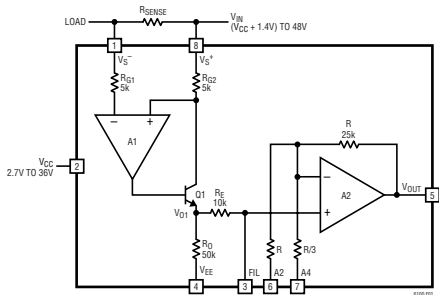
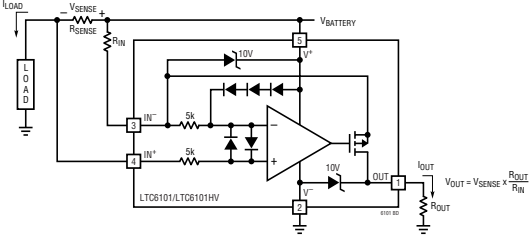
Full-Range Disadvantages

- Wide input common mode voltage swings
- Common mode rejection may limit high frequency accuracy in PWM applications

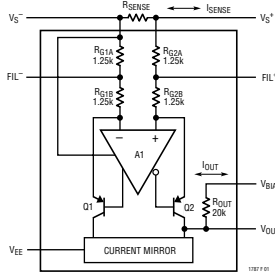
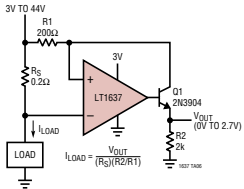
Amplifier Types for Bi-directional Implementation

- Difference amplifiers-LT1990, LT1991, LT1995, LT1996
- Instrumentation amplifiers: LTC2053
- Flying capacitor amplifier: LTC6943

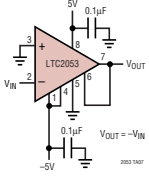
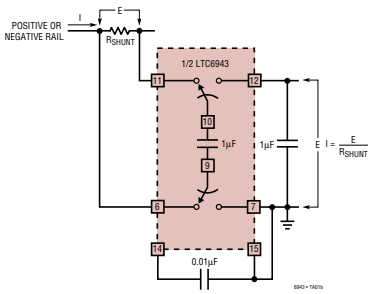
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TYPE/CIRCUIT	GAIN (V/V)	DEVICES AND PACKAGES	ACCURACY		SPEED		V _{SUPPLY} RANGE (V _S)	V _{IN} RANGE (V _{CM})	DIFFERENTIAL V _{IN} RANGE (SURVIVAL)
			OFFSET VOLTAGE (V _{OS})	INPUT CURRENT (I _{BIAS})	BANDWIDTH	SLEW RATE			
<ul style="list-style-type: none"> ■ High Side ■ One Direction ■ Voltage Out 	10 to 50	LT6100 MSOP-8 DFN	300μV	5μA	100kHz	0.05V/μs	2.7V to 36V	(V _S + 1.4V) to 48V	±48V
<ul style="list-style-type: none"> ■ High Side ■ One Direction ■ Current Out 	Resistor Ratio	LTC6101 LTC6101HV SOT23-5 MSOP-8	350μV 350μV	250nA 250nA	200kHz 200kHz	2.5V/μs 2.5V/μs	4V to 70V 4V to 105V	(V _S - 1.5V) to 70V (V _S - 1.5V) to 105V	±70V ±105V

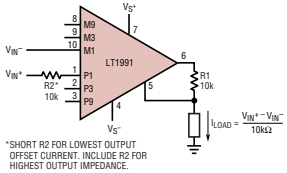
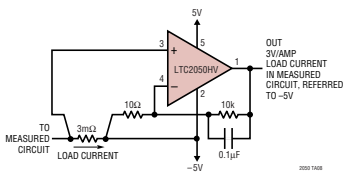
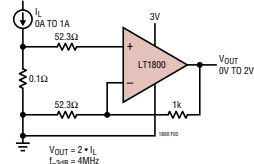
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TYPE/CIRCUIT	GAIN (V/V)	DEVICES AND PACKAGES	ACCURACY		SPEED		V_{SUPPLY} RANGE (V_S)	V_{IN} RANGE (VCM)	DIFFERENTIAL V_{IN} RANGE (SURVIVAL)
			OFFSET VOLTAGE (V_{OS})	INPUT CURRENT (I_{BIAS})	BANDWIDTH	SLEW RATE			
<ul style="list-style-type: none"> High Side Bi-directional Current or Voltage ($R_{OUT} = 20k$) 	Fixed 8 or Scaleable	LT1787 LT1787HV SO-8 MSOP-8	75 μ V 75 μ V	20 μ A 20 μ A	300kHz 300kHz	0.1V/ μ s 0.1V/ μ s	2.5V to 36V 2.5V to 60V	2.5V to 36V 2.5V to 60V	$\pm 10V$ $\pm 10V$
<ul style="list-style-type: none"> High Side One Direction Voltage Out Over the Top Amplifiers 	Resistor Ratio	LT1494 LT1636 LT1637 LT1672 LT1782 LT1783 LT1784 DIP-8 MS-8 SO-8 DFN SOT23-5 SOT23-6	150 μ V 50 μ V 100 μ V 150 μ V 400 μ V 400 μ V 1500 μ V	250pA 5nA 20nA 250pA 8nA 45nA 250nA	3kHz 200kHz 1MHz 12kHz 200kHz 1.25MHz 2.5MHz	0.001V/ μ s 0.07V/ μ s 0.35V/ μ s 0.005V/ μ s 0.07V/ μ s 0.42V/ μ s 2.4V/ μ s	2.1V to 36V 2.6V to 44V 1.8V to 44V 2.1V to 36V 2.2V to 18V 2.2V to 18V 2V to 18V	0 to $V_S + (36V - V_S)$ 0 to $V_S + (44V - V_S)$ 0 to $V_S + (44V - V_S)$ 0 to $V_S + (36V - V_S)$ 0 to $V_S + (18V - V_S)$ 0 to $V_S + (18V - V_S)$ 0 to $V_S + (18V - V_S)$	36V 44V 44V 36V 36V 36V 36V

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TYPE/CIRCUIT	GAIN (V/V)	DEVICES AND PACKAGES	ACCURACY		SPEED		V_{SUPPLY} RANGE (V_S)	V_{IN} RANGE (VCM)	DIFFERENTIAL V_{IN} RANGE (SURVIVAL)
			OFFSET VOLTAGE (V_{OS})	INPUT CURRENT (I_{BIAS})	BANDWIDTH	SLEW RATE			
<ul style="list-style-type: none"> ■ High Side ■ One Direction ■ Voltage Out ■ Instrumentation Amplifier 	Resistor Ratio	LTC2053 LTC6800 DFN MS-8	5µV 5µV	4nA 4nA	200kHz 200kHz	0.2V/µs 0.2V/µs	2.7V to 11V 2.7V to 5.5V	2.7V to 11V 2.7V to 5.5V	5.5V 5.5V
<ul style="list-style-type: none"> ■ High Side or Low Side ■ One Direction ■ Voltage on a capacitor output ■ Flying Capacitor 	Unity	LTC6943 TSSOP – 16		6pA	90kHz		5V to 18V	5V to 18V	18V

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TYPE/CIRCUIT	GAIN (V/V)	DEVICES AND PACKAGES	ACCURACY		SPEED		V _{SUPPLY} RANGE (V _S)	V _{IN} RANGE (V _{CM})	DIFFERENTIAL V _{IN} RANGE (SURVIVAL)
			OFFSET VOLTAGE (V _{OS})	INPUT CURRENT (I _{BIAS})	BANDWIDTH	SLEW RATE			
<ul style="list-style-type: none"> High Side or Low Side Bi-Directional Voltage Out Difference Amplifiers  <p>*SHORT R2 FOR LOWEST OUTPUT OFFSET CURRENT. INCLUDE R2 FOR HIGHEST OUTPUT IMPEDANCE.</p>	1 and 10 1 to 13 1 to 7 9 to 117	LT1990 LT1991 LT1995 LT1996	900μV 15μV 1000μV 15μV	2.5nA 2.5nA	105kHz 110kHz 32MHz 38kHz	0.55V/μs 0.12V/μs 1000V/μs 0.12V/μs	2.4V to 36V 2.7V to 36V 5V to 36V 2.7V to 36V	-250V to 250V -60V to 60V 0V to 36V -60V to 60V	±250V ±60V V _S + 0.3V ±60V
<ul style="list-style-type: none"> Low Side One Direction Voltage Out Zero-Drift Amplifiers 	Resistor Ratio	LTC2050 LTC2054 LTC2054HV	0.5μV 0.5μV 0.5μV	75pA 0.6pA 0.6pA	3MHz 500kHz 500kHz	2V/μs 0.5V/μs 0.5V/μs	2.7V to 7V 2.7V to 7V 2.7V to 12V	0V to (V _S - 1.3V) 0V to (V _S - 0.7V) 0V to (V _S - 0.7V)	V _S + 0.3V V _S + 0.3V V _S + 0.3V
<ul style="list-style-type: none"> Low Side One Direction Voltage Out Rail to Rail I/O Amplifiers  <p>V_{OUT} = 2 • I_L $f_{-3dB} = 4\text{MHz}$ UNCERTAINTY DUE TO V_{OS}, I_B < 4mA</p>	Resistor Ratio	LT1218 LT1677 LT1800 LT1806 LT6200 LT6220	25μV 20μV 75μV 100μV 1400μV 70μV	30nA 2nA 25nA 1μA 10μA 15nA	300kHz 7.2MHz 80MHz 325MHz 110MHz 60MHz	0.1V/μs 2.5V/μs 25V/μs 125V/μs 50V/μs 20V/μs	2V to 36V 2.5V to 44V 2V to 12.6V 1.8V to 12.6V 2.2V to 12.6V 2.2V to 12.6V	0V to V _S 0V to V _S 0V to V _S 0V to V _S 0V to V _S 0V to V _S	V _S + 0.3V V _S + 0.3V V _S + 0.3V V _S + 0.3V V _S + 0.3V V _S + 0.3V

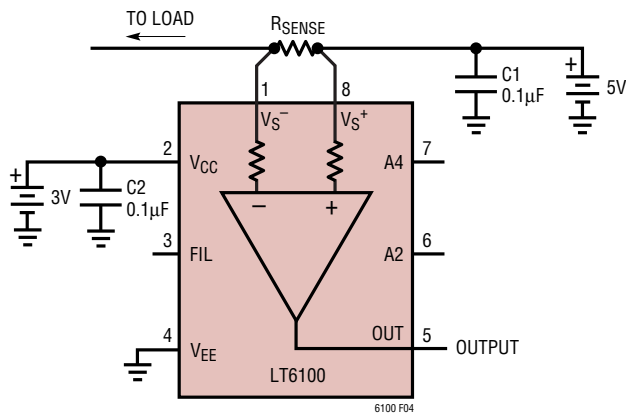
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High Side

This chapter discusses solutions for high side current sensing. With these circuits the total current supplied to a load is monitored in the positive power supply line.

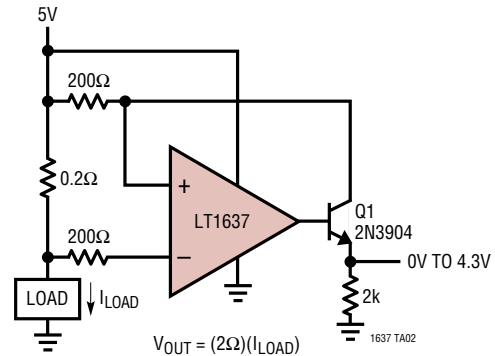
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LT6100 Load Current Monitor



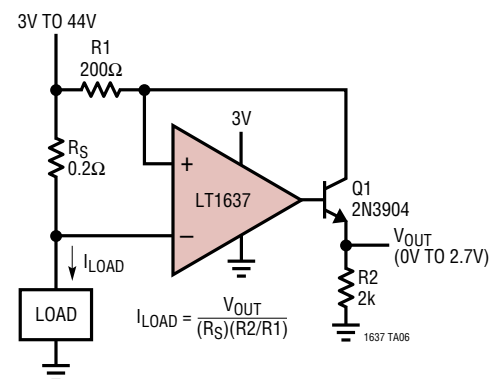
This is the basic LT6100 circuit configuration. The internal circuitry, including an output buffer, typically operates from a low voltage supply, such as the 3V shown. The monitored supply can range anywhere from $V_{CC} + 1.4V$ up to 48V. The A2 and A4 pins can be strapped various ways to provide a wide range of internally fixed gains. The input leads become very hi-Z when V_{CC} is powered down, so as not to drain batteries for example. Access to an internal signal node (pin 3) provides an option to include a filtering function with one added capacitor. Small-signal range is limited by V_{OL} in single-supply operation.

“Classic” Positive Supply Rail Current Sense



This circuit uses generic devices to assemble a function similar to an LTC6101. A Rail-to-Rail Input type op amp is required since input voltages are right at the upper rail. The circuit shown here is capable of monitoring up to 44V applications. Besides the complication of extra parts, the V_{OS} performance of op amps at the supply is generally not factory trimmed, thus less accurate than other solutions. The finite current gain of the bipolar transistor is a small source of gain error.

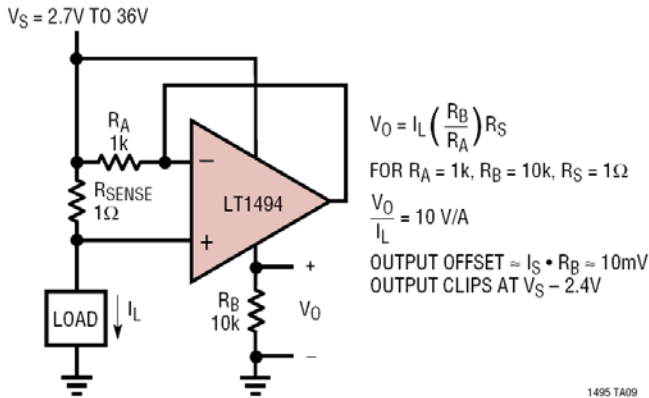
Over-The-Top Current Sense



This circuit is a variation on the “classic” high-side circuit, but takes advantage of Over-the-Top input capability to separately supply the IC from a low-voltage rail. This provides a measure of fault protection to downstream circuitry by virtue of the limited output swing set by the low-voltage supply. The disadvantage is V_{OS} in the Over-the-Top mode is generally inferior to other modes, thus less accurate. The finite current gain of the bipolar transistor is a source of small gain error.

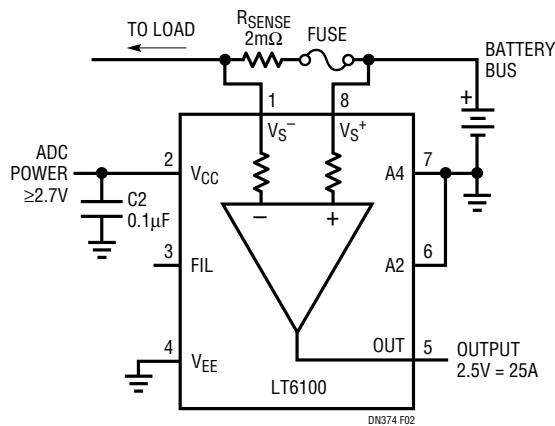
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Self-Powered High Side Current Sense



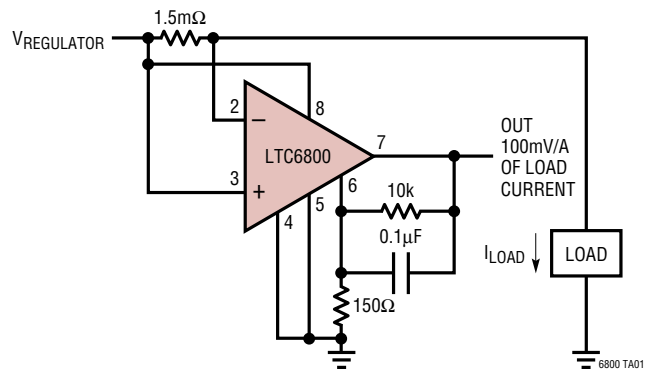
This circuit takes advantage of the microampere supply current and Rail-to-Rail input of the LT1494. The circuit is simple because the supply draw is essentially equal to the load current developed through R_A . This supply current is simply passed through R_B to form an output voltage that is appropriately amplified.

High Side Current Sense and Fuse Monitor



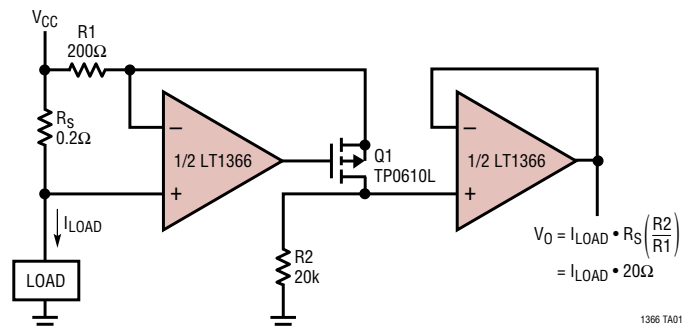
The LT6100 can be used as a combination current sensor and fuse monitor. This part includes on-chip output buffering and was designed to operate with the low supply voltage ($\geq 2.7V$), typical of vehicle data acquisition systems, while the sense inputs monitor signals at the higher battery bus potential. The LT6100 inputs are tolerant of large input differentials, thus allowing the blown-fuse operating condition (this would be detected by an output full-scale indication). The LT6100 can also be powered down while maintaining high impedance sense inputs, drawing less than $1\mu A$ max from the battery bus.

Precision High Side Power Supply Current Sense



This is a low-voltage, ultra-high-precision monitor featuring a Zero-Drift Instrumentation Amplifier (IA) that provides Rail-to-Rail inputs and outputs. Voltage gain is set by the feedback resistors. Accuracy of this circuit is set by the quality of resistors selected by the user, small-signal range is limited by V_{OL} in single-supply operation. The voltage rating of this part restricts this solution to applications of $< 5.5V$. This IA is sampled, so the output is discontinuous with input changes, thus only suited to very low frequency measurements.

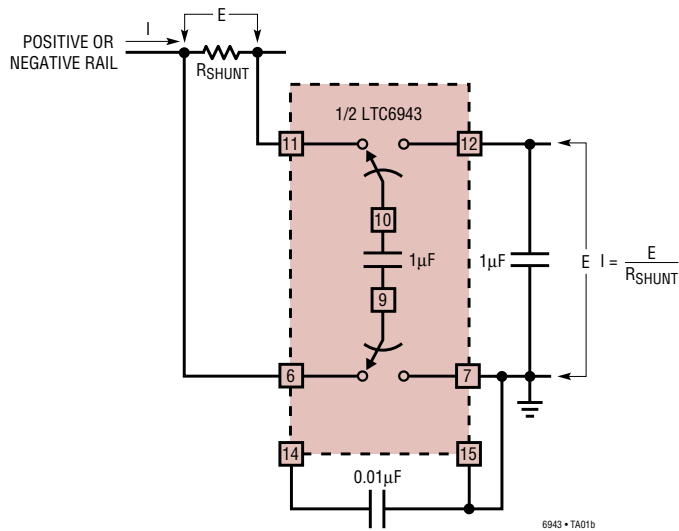
Positive Supply Rail Current Sense



This is a configuration similar to an LT6100 implemented with generic components. A Rail-to-Rail or Over-the-Top input op amp type is required (for the first section). The first section is a variation on the classic high-side where the P-MOSFET provides an accurate output current into R_2 (compared to a BJT). The second section is a buffer to allow driving ADC ports, etc., and could be configured with gain if needed. As shown, this circuit can handle up to $36V$ operation. Small-signal range is limited by V_{OL} in single-supply operation.

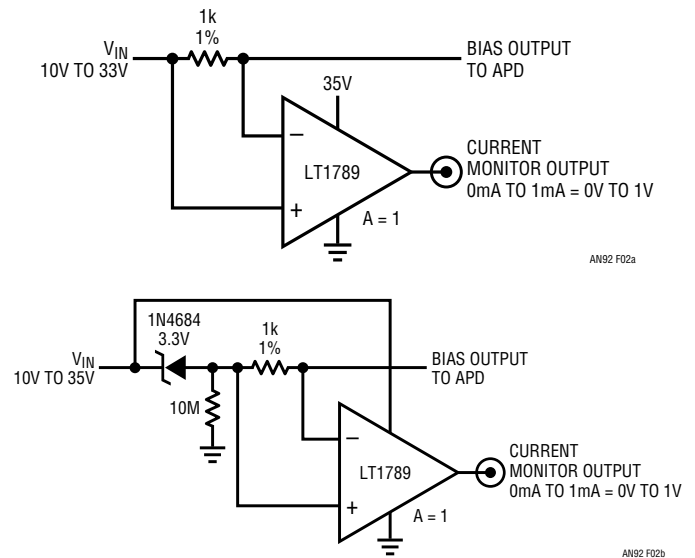
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Precision Current Sensing in Supply Rails



This is the same sampling architecture as used in the front-end of the LTC2053 and LTC6800, but sans op amp gain stage. This particular switch can handle up to 18V, so the ultra-high precision concept can be utilized at higher voltages than the fully integrated ICs mentioned. This circuit simply commutates charge from the flying sense capacitor to the ground-referenced output capacitor so that under dc input conditions the single-ended output voltage is exactly the same as the differential across the sense resistor. A high precision buffer amplifier would typically follow this circuit (such as an LTC2054). The commutation rate is user-set by the capacitor connected to pin 14. For negative supply monitoring, pin 15 would be tied to the negative rail rather than ground.

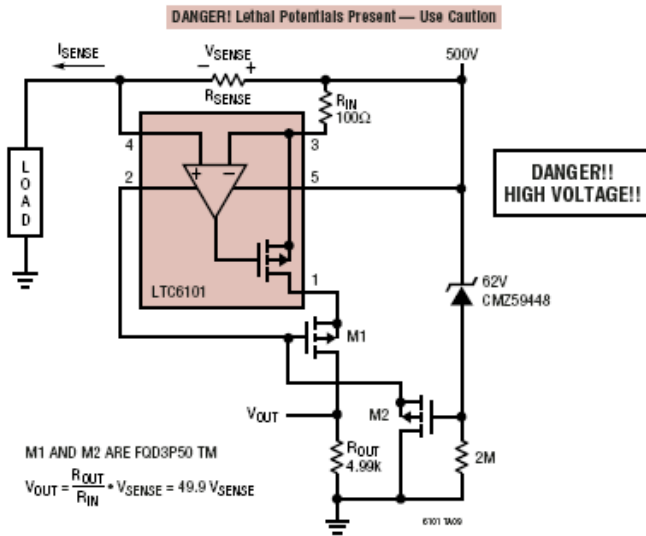
Measuring bias current into an Avalanche Photo Diode (APD) using an instrumentation amplifier.



The upper circuit uses an instrumentation amplifier (IA) powered by a separate rail ($>1V$ above V_{IN}) to measure across the 1k Ω current shunt. The lower figure is similar but derives its power supply from the APD bias line. The limitation of these circuits is the 35V maximum APD voltage, whereas some APDs may require 90V or more. In the single-supply configuration shown, there is also a dynamic range limitation due to V_{OL} to consider. The advantage of this approach is the high accuracy that is available in an IA.

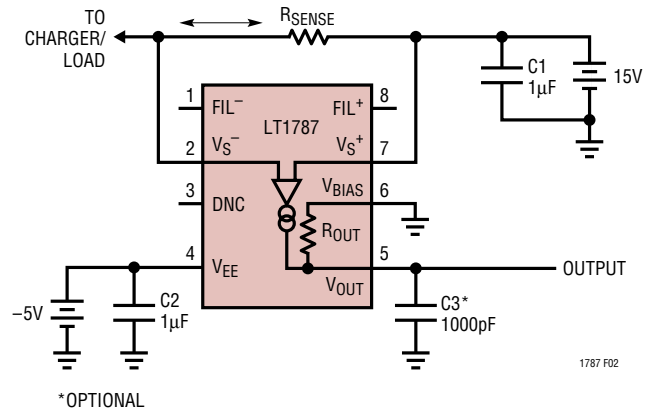
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Simple 500V Current Monitor



Adding two external Mosfets to hold off the voltage allows the LTC6101 to connect to very high potentials and monitor the current flow. The output current from the LTC6101, which is proportional to the sensed input voltage, flows through M1 to create a ground referenced output voltage.

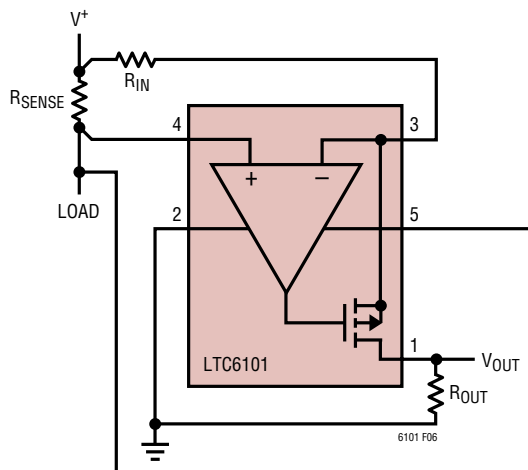
Bidirectional Battery-Current Monitor



This circuit provides the capability of monitoring current in either direction through the sense resistor. To allow negative outputs to represent charging current, V_{EE} is connected to a small negative supply. In single-supply operation (V_{EE} at ground), the output range may be offset upwards by applying a positive reference level to V_{BIAS} (1.25V for example). $C3$ may be used to form a filter in conjunction with the output resistance (R_{OUT}) of the part. This solution offers excellent precision (very low V_{OS}) and a fixed nominal gain of 8.

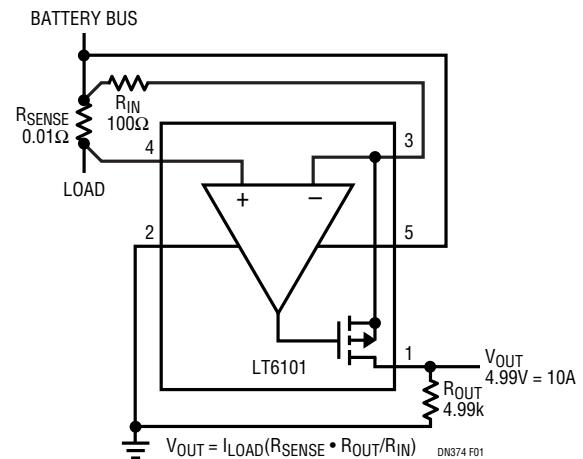
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LTC6101 Supply Current included as Load in Measurement



This is the basic LTC6101 high-side sensing supply-monitor configuration, where the supply current drawn by the IC is included in the readout signal. This configuration is useful when the IC current may not be negligible in terms of overall current draw, such as in low-power battery-powered applications. R_{SENSE} should be selected to limit voltage-drop to $<500\text{mV}$ for best linearity. If it is desirable not to include the IC current in the readout, as in load monitoring, pin 5 may be connected directly to V^+ instead of the load. Gain accuracy of this circuit is limited only by the precision of the resistors selected by the user.

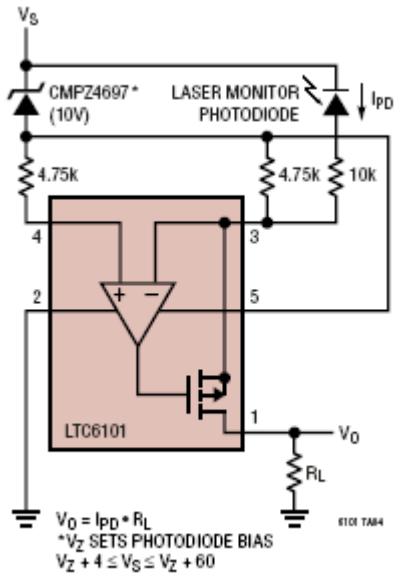
Simple High Side Current Sense Using the LTC6101



This is a basic high side current monitor using the LTC6101. The selection of R_{IN} and R_{OUT} establishes the desired gain of this circuit, powered directly from the battery bus. The current output of the LTC6101 allows it to be located remotely to R_{OUT} . Thus, the amplifier can be placed directly at the shunt, while R_{OUT} is placed near the monitoring electronics without ground drop errors. This circuit has a fast $1\mu\text{s}$ response time that makes it ideal for providing MOSFET load switch protection. The switch element may be the high side type connected between the sense resistor and the load, a low side type between the load and ground or an H-bridge. The circuit is programmable to produce up to 1mA of full-scale output current into R_{OUT} , yet draws a mere $250\mu\text{A}$ supply current when the load is off.

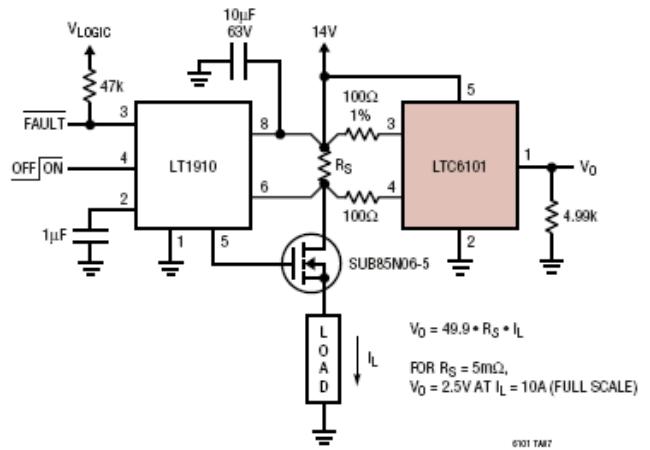
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High-Side Transimpedance Amplifier



Current through a photodiode with a large reverse bias potential is converted to a ground referenced output voltage directly through an LTC6101. The supply rail can be as high as 70V. Gain of the I to V conversion, the transimpedance, is set by the selection of resistor R_L .

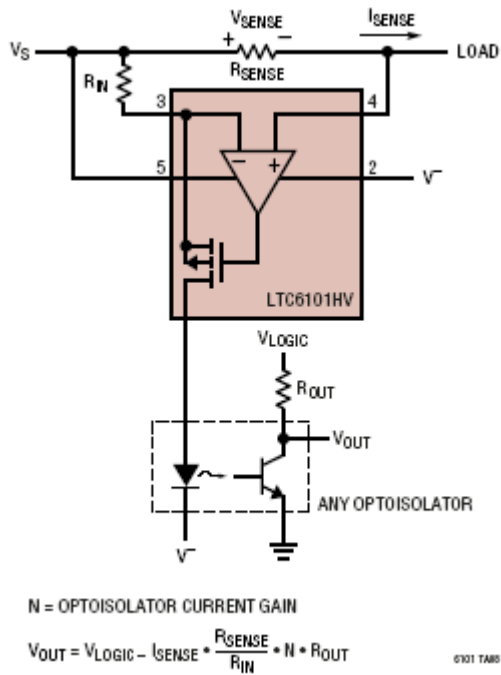
Intelligent High Side Switch



The LT1910 is a dedicated high side MOSFET driver with built in protection features. It provides the gate drive for a power switch from standard logic voltage levels. It provides shorted load protection by monitoring the current flow to through the switch. Adding an LTC6101 to the same circuit, sharing the same current sense resistor, provides a linear voltage signal proportional to the load current for additional intelligent control.

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48V Supply Current Monitor with Isolated Output and 105V Survivability



The HV version of the LTC6101 can operate with a total supply voltage of 105V. Current flow in high supply voltage rails can be monitored directly or in an isolated fashion as shown in this circuit. The gain of the circuit and the level of output current from the LTC6101 depends on the particular opto-isolator used.

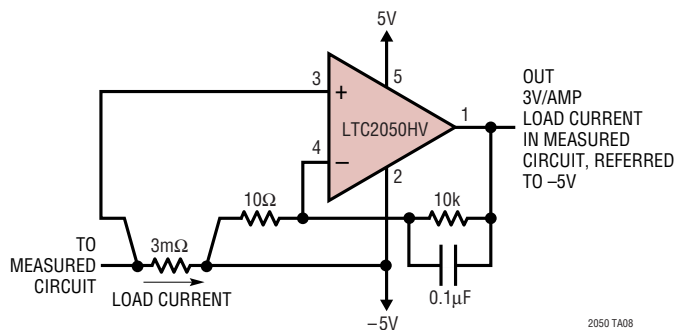
APPLICATION NOTE 105: Current Sense Circuit Collection

Low Side

This chapter discusses solutions for low side current sensing. With these circuits the current flowing in the ground return or negative power supply line is monitored.

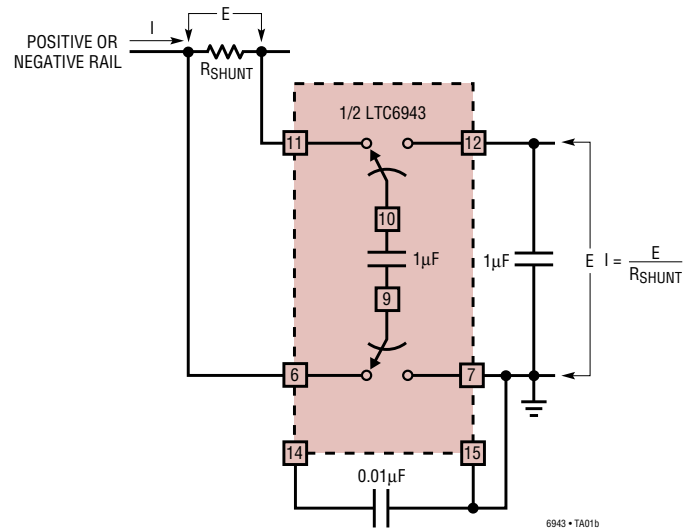
To see other chapters in this Application Note, return to the [Introduction](#).

“Classic” High-Precision Low Side Current Sense



This configuration is basically a standard non-inverting amplifier. The op amp used must support common-mode operation at the lower rail and the use of a Zero-Drift type (as shown) provides excellent precision. The output of this circuit is referenced to the lower Kelvin contact, which could be ground in a single-supply application. Small-signal range is limited by V_{OL} for single-supply designs. Scaling accuracy is set by the quality of the user-selected resistors.

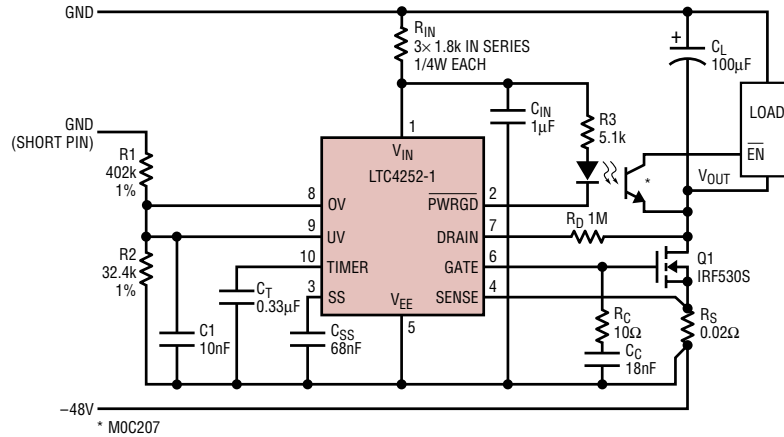
Precision Current Sensing in Supply Rails



This is the same sampling architecture as used in the front-end of the LTC2053 and LTC6800, but sans op amp gain stage. This particular switch can handle up to 18V, so the ultra-high precision concept can be utilized at higher voltages than the fully integrated ICs mentioned. This circuit simply commutates charge from the flying sense capacitor to the ground-referenced output capacitor so that under dc input conditions the single-ended output voltage is exactly the same as the differential across the sense resistor. A high precision buffer amplifier would typically follow this circuit (such as an LTC2054). The commutation rate is user-set by the capacitor connected to pin 14. For negative supply monitoring, pin 15 would be tied to the negative rail rather than ground.

APPLICATION NOTE 105: Current Sense Circuit Collection

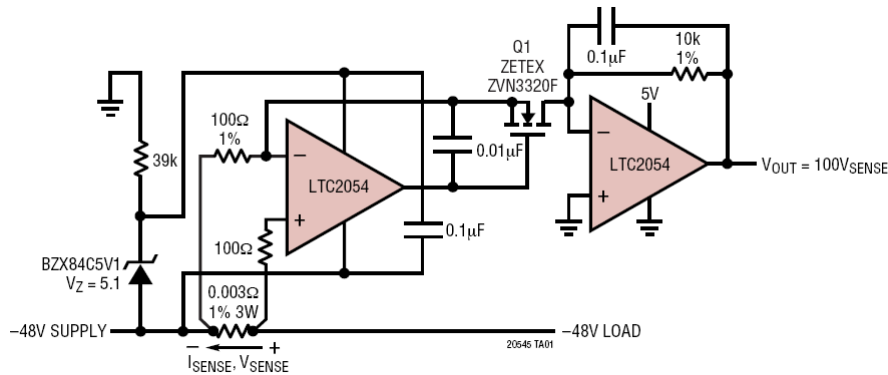
-48V Hot Swap Controller



This load protecting circuit employs low-side current sensing. The N-MOSFET is controlled to soft-start the load (current ramping) or to disconnect the load in the

event of supply or load faults. An internal shunt regulator establishes a local operating voltage.

-48V Low Side Precision Current Sense

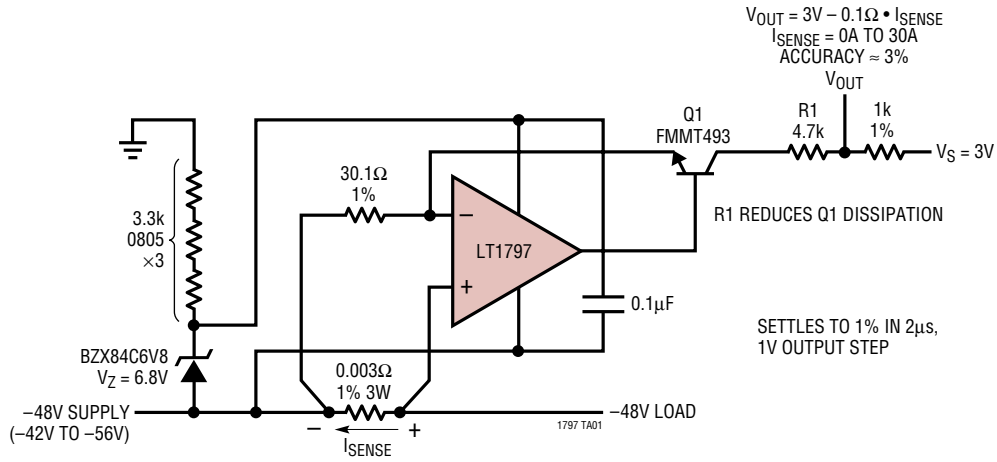


The first stage amplifier is basically a complementary form of the “classic” high-side current sense, designed to operate with telecom negative supply voltage. The Zener forms an inexpensive “floating” shunt-regulated supply for the first op amp. The N-MOSFET drain delivers a metered current into the virtual ground of the second stage, configured as a trans-impedance amplifier (TIA). The second op amp is powered from a positive supply

and furnishes a positive output voltage for increasing load current. . A dual op amp cannot be used for this implementation due to the different supply voltages for each stage. This circuit is exceptionally precise due to the use of Zero Drift op amps. The scaling accuracy is established by the quality of the user-selected resistors. Small-signal range is limited by V_{OL} in single-supply operation of the second stage.

APPLICATION NOTE 105: Current Sense Circuit Collection

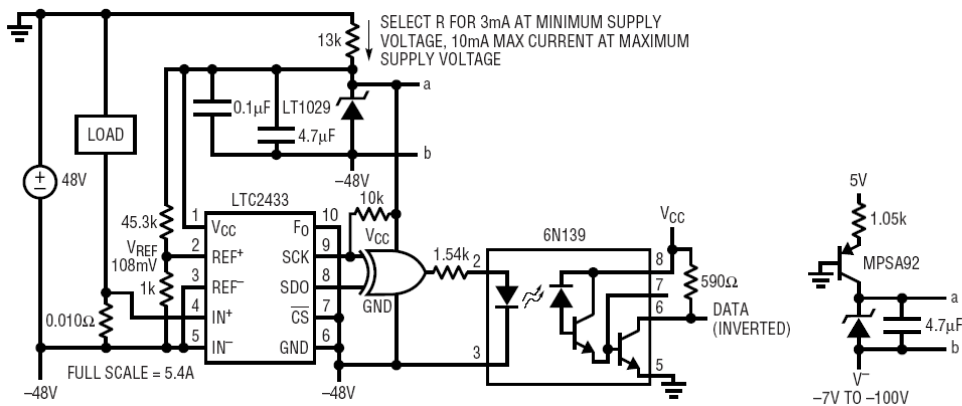
Fast Compact -48V Current Sense



This amplifier configuration is essentially the complementary implementation to the classic high-side configuration. The op amp used must support common-mode operation at its lower rail. A “floating” shunt-regulated local supply is provided by the Zener diode, and the transistor provides metered current to an output load resis-

tance (1kΩ in this circuit). In this circuit, the output voltage is referenced to a positive potential and moves downward when representing increasing -48V loading. Scaling accuracy is set by the quality of resistors used and the performance of the NPN transistor.

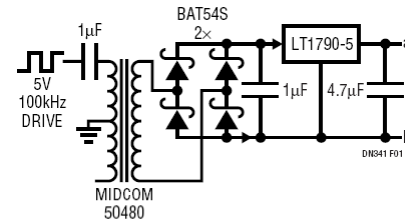
-48V Current Monitor



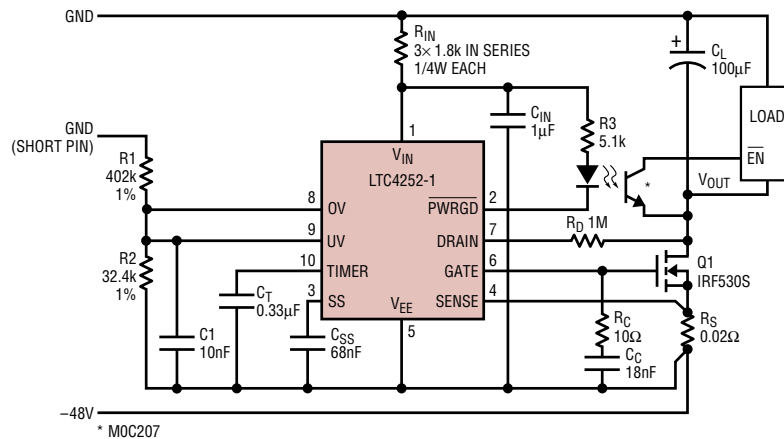
APPLICATION NOTE 105: Current Sense Circuit Collection

In this circuit an economical ADC is used to acquire the sense resistor voltage drop directly. The converter is powered from a “floating” high-accuracy shunt-regulated supply and is configured to perform continuous conversions. The ADC digital output drives an opto-isolator, level-shifting the serial data stream to ground. For wider supply voltage applications, the 13k biasing resistor may be replaced with an active 4mA current source such as shown to the right. For complete dielectric isolation

and/or higher efficiency operation, the ADC may be powered from a small transformer circuit as shown below.



-48V Hot Swap Controller

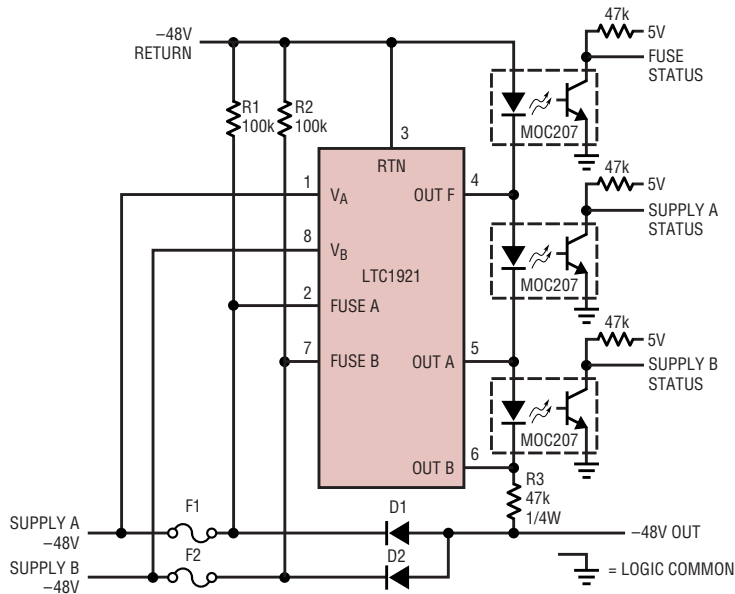


This load protecting circuit employs low-side current sensing. The N-MOSFET is controlled to soft-start the load (current ramping) or to disconnect the load in the

event of supply or load faults. An internal shunt regulator establishes a local operating voltage.

APPLICATION NOTE 105: Current Sense Circuit Collection

Simple Telecom Power Supply Fuse Monitor



V _A	V _B	SUPPLY A STATUS	SUPPLY B STATUS
OK	OK	0	0
OK	UV OR OV	0	1
UV OR OV	OK	1	0
UV OR OV	UV OR OV	1	1

OK: WITHIN SPECIFICATION

OV: OVERVOLTAGE

UV: UNDERVOLTAGE

V _{FUSE A}	V _{FUSE B}	FUSE STATUS
= V _A	= V _B	0
= V _A	≠ V _B	1
≠ V _A	= V _B	1
≠ V _A	≠ V _B	1*

0: LED/PHOTODIODE ON

1: LED/PHOTODIODE OFF

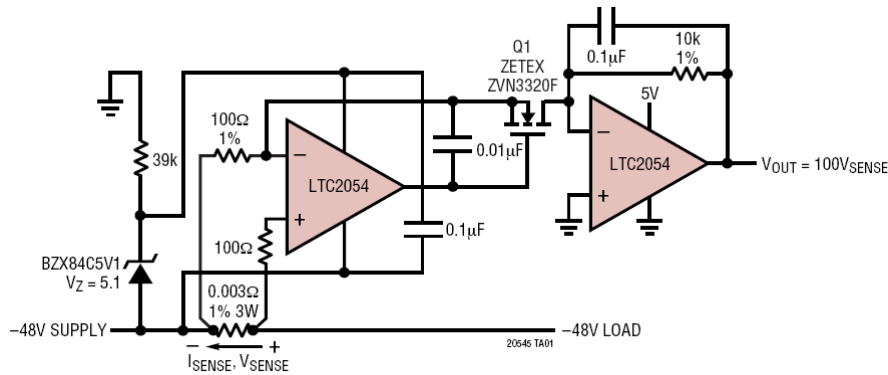
*IF BOTH FUSES (F1 AND F2) ARE OPEN, ALL STATUS OUTPUTS WILL BE HIGH SINCE R3 WILL NOT BE POWERED

The LTC1921 provides an all-in-one telecom fuse and supply-voltage monitoring function. Three opto-isolated

status flags are generated that indicate the condition of the supplies and the fuses.

APPLICATION NOTE 105: Current Sense Circuit Collection

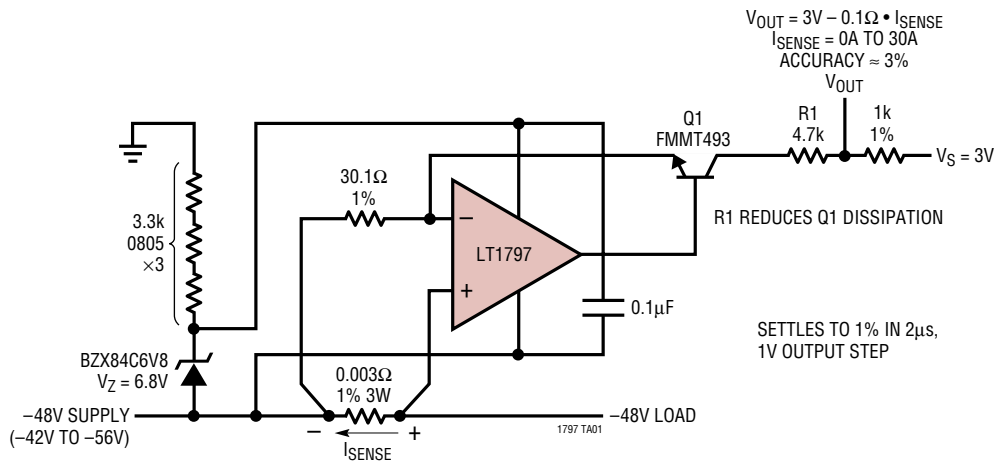
-48V Low Side Precision Current Sense



The first stage amplifier is basically a complementary form of the “classic” high-side current sense, designed to operate with telecom negative supply voltage. The Zener forms an inexpensive “floating” shunt-regulated supply for the first op amp. The N-MOSFET drain delivers a metered current into the virtual ground of the second stage, configured as a trans-impedance amplifier (TIA). The second op amp is powered from a positive supply

and furnishes a positive output voltage for increasing load current. . A dual op amp cannot be used for this implementation due to the different supply voltages for each stage. This circuit is exceptionally precise due to the use of Zero Drift op amps. The scaling accuracy is established by the quality of the user-selected resistors. Small-signal range is limited by V_{OL} in single-supply operation of the second stage.

Fast Compact -48V Current Sense

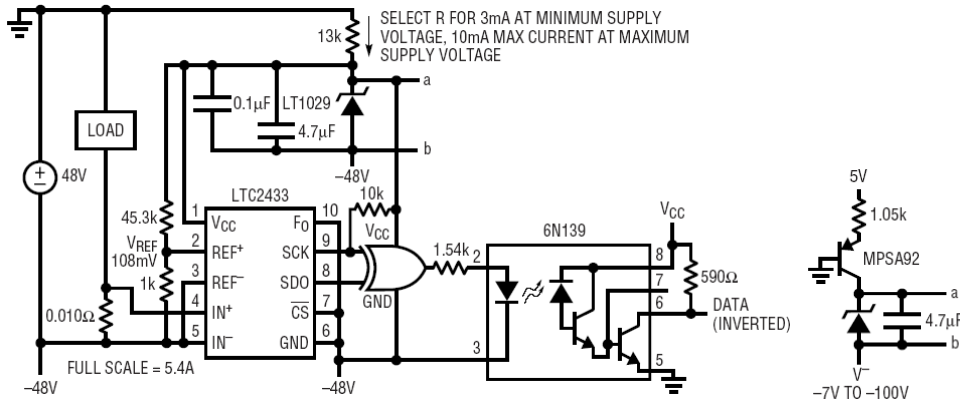


This amplifier configuration is essentially the complementary implementation to the classic high-side configuration. The op amp used must support common-mode operation at its lower rail. A “floating” shunt-regulated local supply is provided by the Zener diode, and the transistor provides metered current to an output load resis-

tance (1k Ω in this circuit). In this circuit, the output voltage is referenced to a positive potential and moves downward when representing increasing -48V loading. Scaling accuracy is set by the quality of resistors used and the performance of the NPN transistor.

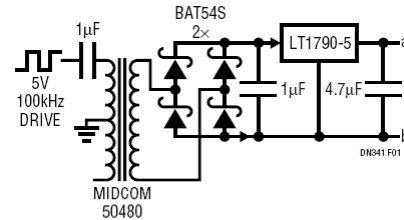
APPLICATION NOTE 105: Current Sense Circuit Collection

-48V Current Monitor

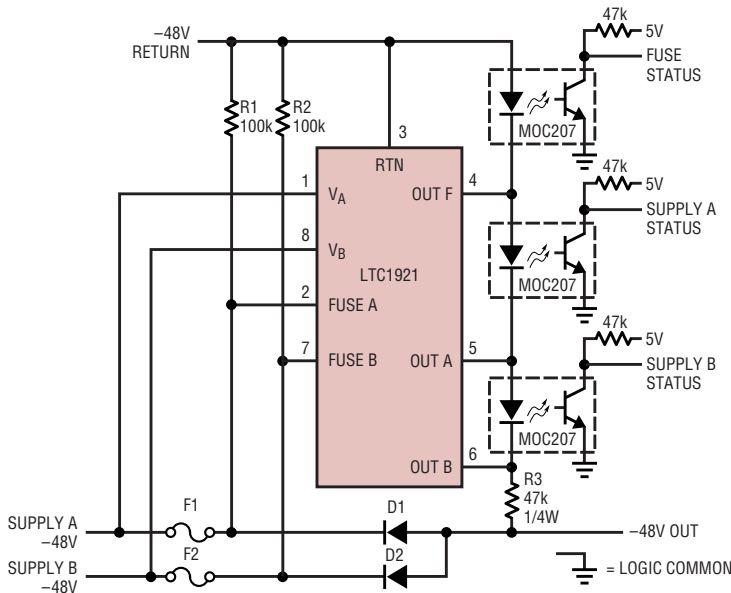


In this circuit an economical ADC is used to acquire the sense resistor voltage drop directly. The converter is powered from a “floating” high-accuracy shunt-regulated supply and is configured to perform continuous conversions. The ADC digital output drives an opto-isolator, level-shifting the serial data stream to ground. For wider supply voltage applications, the 13k biasing resistor may be replaced with an active 4mA current source as shown to the right. For complete dielectric isolation

and/or higher efficiency operation, the ADC may be powered from a small transformer circuit as shown below.



Simple Telecom Power Supply Fuse Monitor



V _A	V _B	SUPPLY A STATUS	SUPPLY B STATUS
OK	OK	0	0
OK	UV OR OV	0	1
UV OR OV	OK	1	0
UV OR OV	UV OR OV	1	1

OK: WITHIN SPECIFICATION
 OV: OVERVOLTAGE
 UV: UNDERVOLTAGE

V _{FUSE A}	V _{FUSE B}	FUSE STATUS
= V _A	= V _B	0
= V _A	≠ V _B	1
≠ V _A	= V _B	1
≠ V _A	≠ V _B	1*

0: LED/PHOTODIODE ON
 1: LED/PHOTODIODE OFF
 *IF BOTH FUSES (F1 AND F2) ARE OPEN,
 ALL STATUS OUTPUTS WILL BE HIGH
 SINCE R3 WILL NOT BE POWERED

The LTC1921 provides an all-in-one telecom fuse and supply-voltage monitoring function. Three opto-isolated

status flags are generated that indicate the condition of the supplies and the fuses.

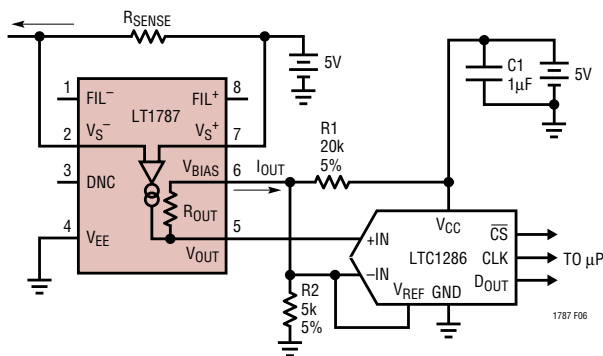
APPLICATION NOTE 105: Current Sense Circuit Collection

Unidirectional

Unidirectional current sensing monitors the current flowing only in one direction through a sense resistor.

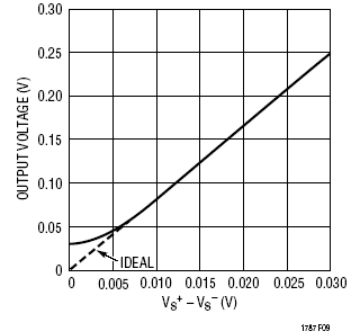
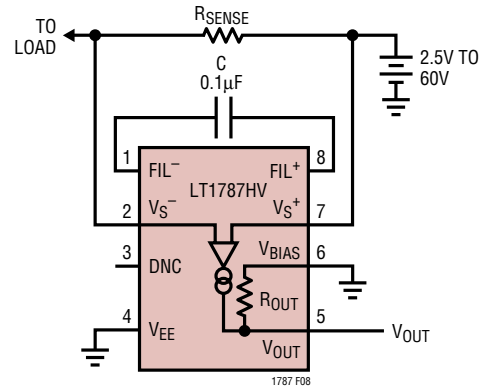
To see other chapters in this Application Note, return to the [Introduction](#).

Unidirectional Output into A/D with Fixed Supply at V_S^+



Here the LT1787 is operating with the LTC1286 A/D converter. The $-IN$ pin of the A/D converter is biased at 1V by the resistor divider R_1 and R_2 . This voltage increases as sense current increases, with the amplified sense voltage appearing between the A/D converter's $-IN$ and $+IN$ terminals. The LTC1286 converter uses sequential sampling of its $-IN$ and $+IN$ inputs. Accuracy is degraded if the inputs move between sampling intervals. A filter capacitor from FIL^+ to FIL^- as well as a filter capacitor from V_{BIAS} to V_{OUT} may be necessary if the sensed current changes more than 1LSB within a conversion cycle.

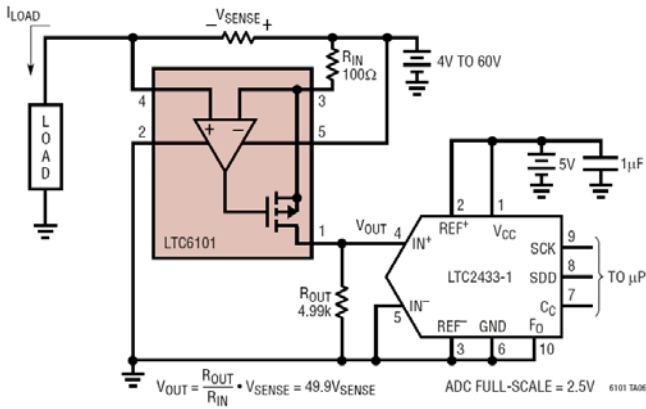
Unidirectional Current Sensing Mode



This is just about the simplest connection in which the LT1787 may be used. The V_{BIAS} pin is connected to ground, and the V_{OUT} pin swings positive with increasing sense current. The output can swing as low as 30mV. Accuracy is sacrificed at small output levels, but this is not a limitation in protection circuit applications or where sensed currents do not vary greatly. Increased low level accuracy can be obtained by level shifting V_{BIAS} above ground. The level shifting may be done with resistor dividers, voltage references or a simple diode. Accuracy is ensured if the output signal is sensed differentially between V_{BIAS} and V_{OUT} .

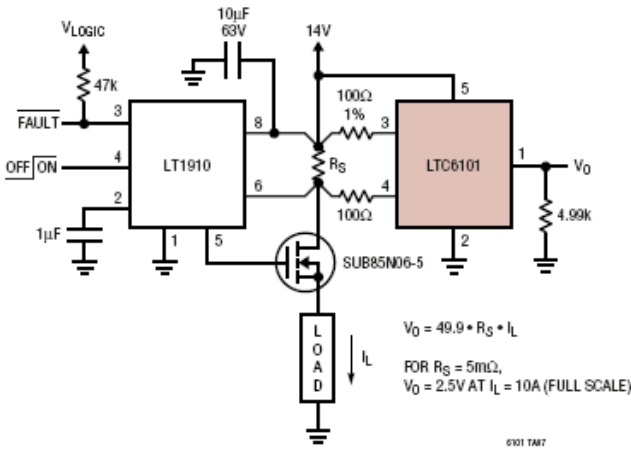
APPLICATION NOTE 105: Current Sense Circuit Collection

16-Bit Resolution Unidirectional Output into LTC2433 ADC



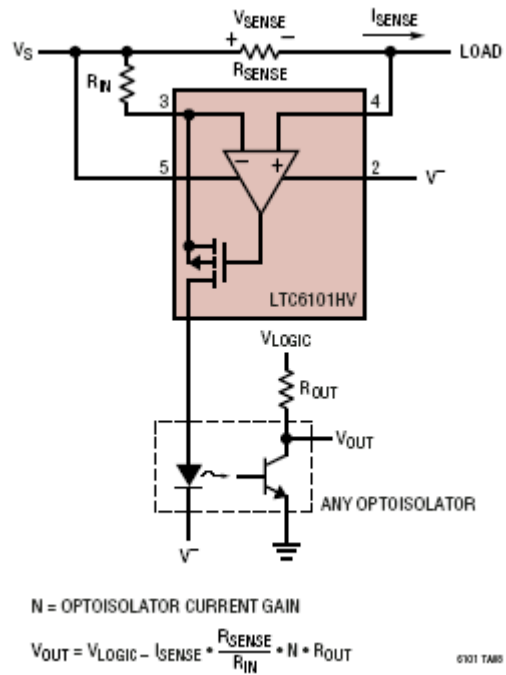
The LTC2433-1 can accurately digitize signal with source impedances up to 5kΩ. This LTC6101 current sense circuit uses a 4.99kΩ output resistance to meet this requirement, thus no additional buffering is necessary.

Intelligent High Side Switch



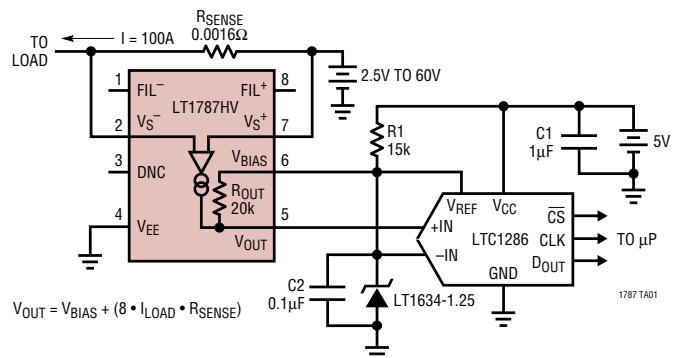
The LT1910 is a dedicated high side MOSFET driver with built in protection features. It provides the gate drive for a power switch from standard logic voltage levels. It provides shorted load protection by monitoring the current flow to through the switch. Adding an LTC6101 to the same circuit, sharing the same current sense resistor, provides a linear voltage signal proportional to the load current for additional intelligent control.

48V Supply Current Monitor with Isolated Output and 105V Survivability



The HV version of the LTC6101 can operate with a total supply voltage of 105V. Current flow in high supply voltage rails can be monitored directly or in an isolated fashion as shown in this circuit. The gain of the circuit and the level of output current from the LTC6101 depends on the particular opto-isolator used.

12-Bit Resolution Unidirectional Output into LTC1286 ADC



While the LT1787 is able to provide a bidirectional output, in this application the economical LTC1286 is used to digitize a unidirectional measurement. The LT1787 has a nominal gain of eight, providing a 1.25V full-scale output at approximately 100A of load current.

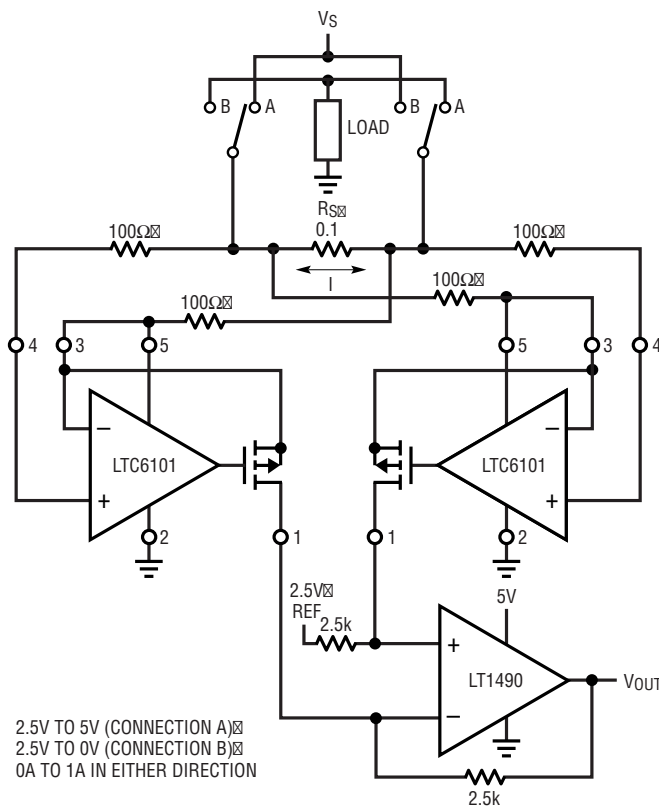
APPLICATION NOTE 105: Current Sense Circuit Collection

Bidirectional

Bidirectional current sensing monitors current flow in both directions through a sense resistor.

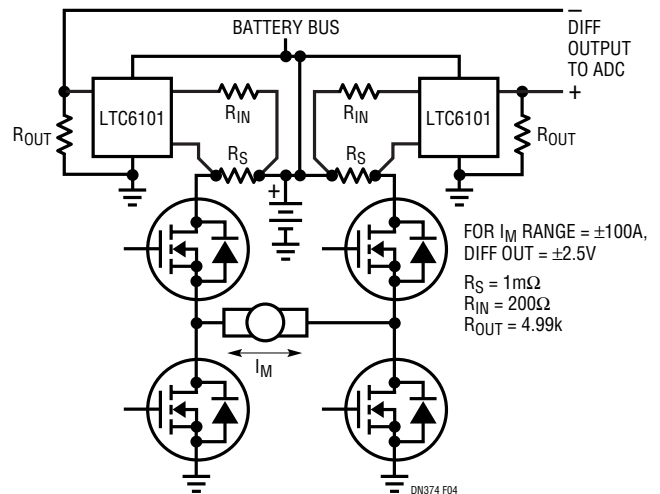
To see other chapters in this Application Note, return to the [Introduction](#).

Bidirectional Current Sensing with Single Ended Output



Two LTC6101's are used to monitor the current in a load in either direction. Using a separate rail-to-rail op amp to combine the two outputs provides a single ended output. With zero current flowing the output sits at the reference potential, one-half the supply voltage for maximum output swing or 2.5V as shown. With power supplied to the load through connection A the output will move positive between 2.5V and V_{cc} . With connection B the output moves down between 2.5V and 0V.

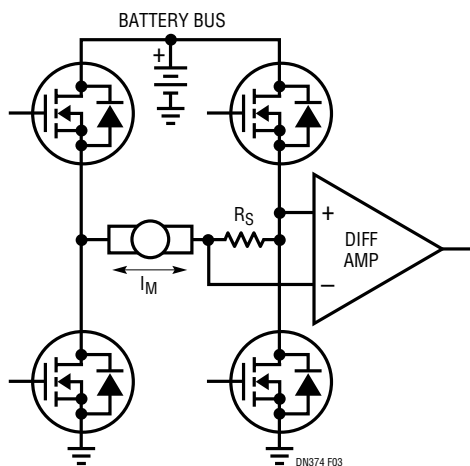
Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information



This circuit implements a differential load measurement for an ADC using twin unidirectional sense measurements. Each LTC6101 performs high side sensing that rapidly responds to fault conditions, including load shorts and MOSFET failures. Hardware local to the switch module (not shown in the diagram) can provide the protection logic and furnish a status flag to the control system. The two LTC6101 outputs taken differentially produce a bidirectional load measurement for the control servo. The ground-referenced signals are compatible with most $\Delta\Sigma$ ADCs. The $\Delta\Sigma$ ADC circuit also provides a "free" integration function that removes PWM content from the measurement. This scheme also eliminates the need for analog-to-digital conversions at the rate needed to support switch protection, thus reducing cost and complexity.

APPLICATION NOTE 105: Current Sense Circuit Collection

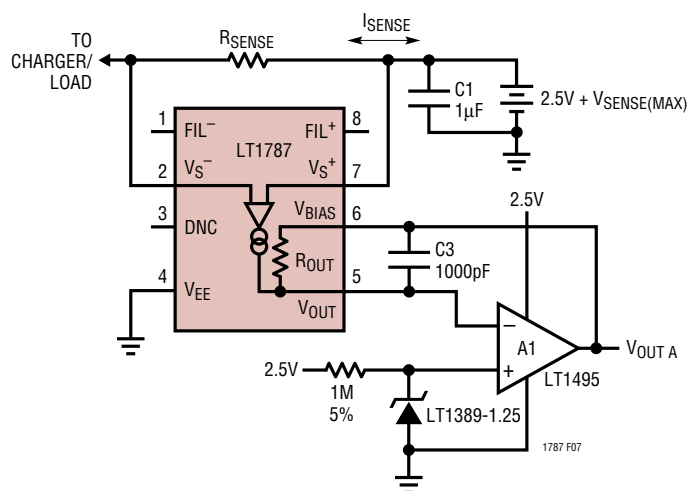
Conventional H-Bridge Current Monitor



Many of the newer electric drive functions, such as steering assist, are bidirectional in nature. These functions are generally driven by H-bridge MOSFET arrays using pulse-width-modulation (PWM) methods to vary the commanded torque. In these systems, there are two main purposes for current monitoring. One is to monitor the current in the load, to track its performance against the desired command (i.e., closed-loop servo law), and another is for fault detection and protection features.

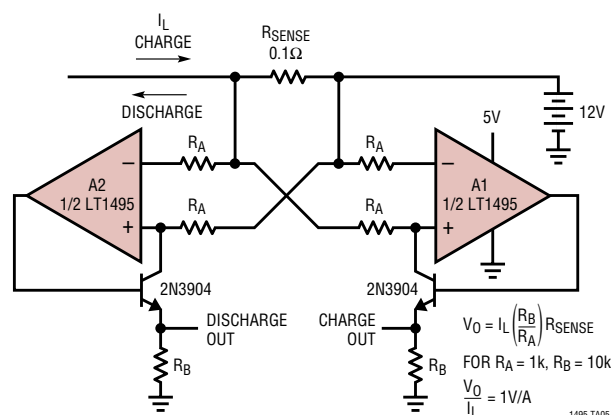
A common monitoring approach in these systems is to amplify the voltage on a “flying” sense resistor, as shown. Unfortunately, several potentially hazardous fault scenarios go undetected, such as a simple short to ground at a motor terminal. Another complication is the noise introduced by the PWM activity. While the PWM noise may be filtered for purposes of the servo law, information useful for protection becomes obscured. The best solution is to simply provide two circuits that individually protect each half-bridge and report the bidirectional load current. In some cases, a smart MOSFET bridge driver may already include sense resistors and offer the protection features needed. In these situations, the best solution is the one that derives the load information with the least additional circuitry.

Single Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter



The LT1787’s output is buffered by an LT1495 rail-to-rail op-amp configured as an I/V converter. This configuration is ideal for monitoring very low voltage supplies. The LT1787’s V_{OUT} pin is held equal to the reference voltage appearing at the op amp’s non-inverting input. This allows one to monitor supply voltages as low as 2.5V. The op-amp’s output may swing from ground to its positive supply voltage. The low impedance output of the op amp may drive following circuitry more effectively than the high output impedance of the LT1787. The I/V converter configuration also works well with split supply voltages.

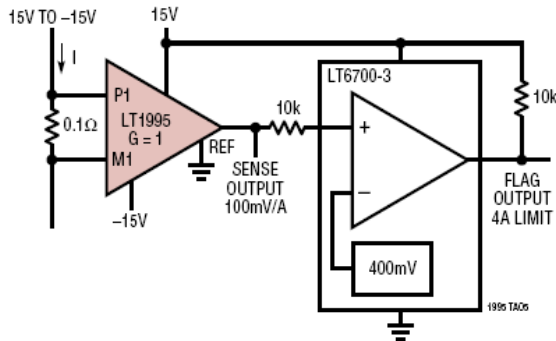
Battery Current Monitor



One LT1495 dual op-amp package can be used to establish separate charge and discharge current monitoring outputs. The LT1495 features Over-the-Top operation allowing the battery potential to be as high as 36V with only a 5V amplifier supply voltage.

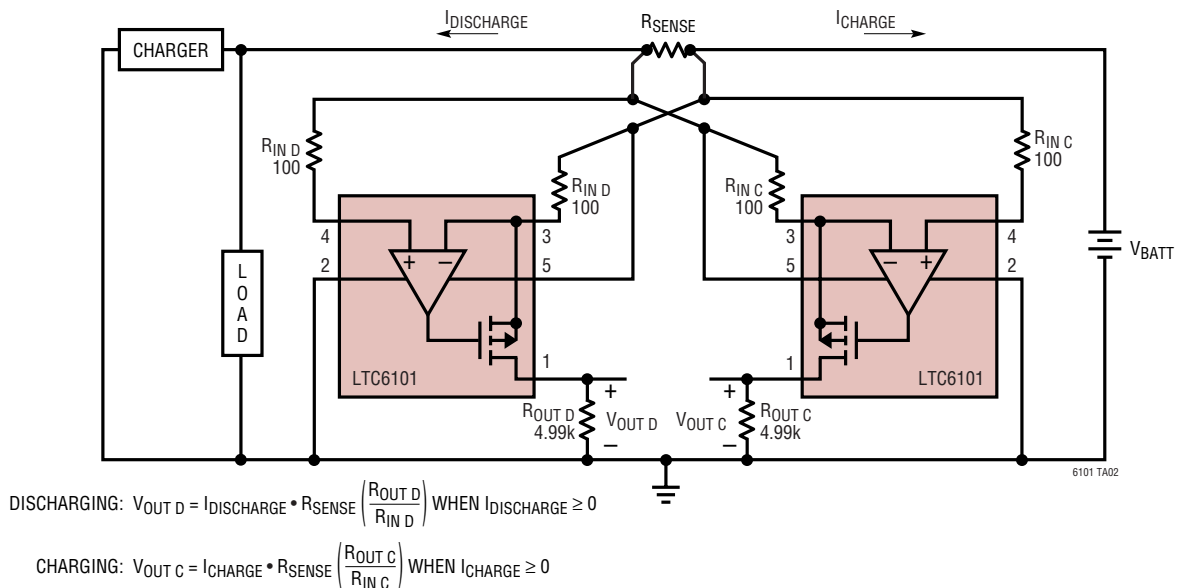
APPLICATION NOTE 105: Current Sense Circuit Collection

Fast Current Sense with Alarm



The LT1995 is shown as a simple unity gain difference amplifier. When biased with split supplies the input current can flow in either direction providing an output voltage of 100mV per Amp from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/usec slew rate the response of this sense amplifier is fast. Adding a simple comparator with a built in reference voltage circuit such as the LT6700-3 can be used to generate an over-current flag. With the 400mV reference the flag occurs at 4A.

Bidirectional Current Sense with Separate Charge/Discharge Output

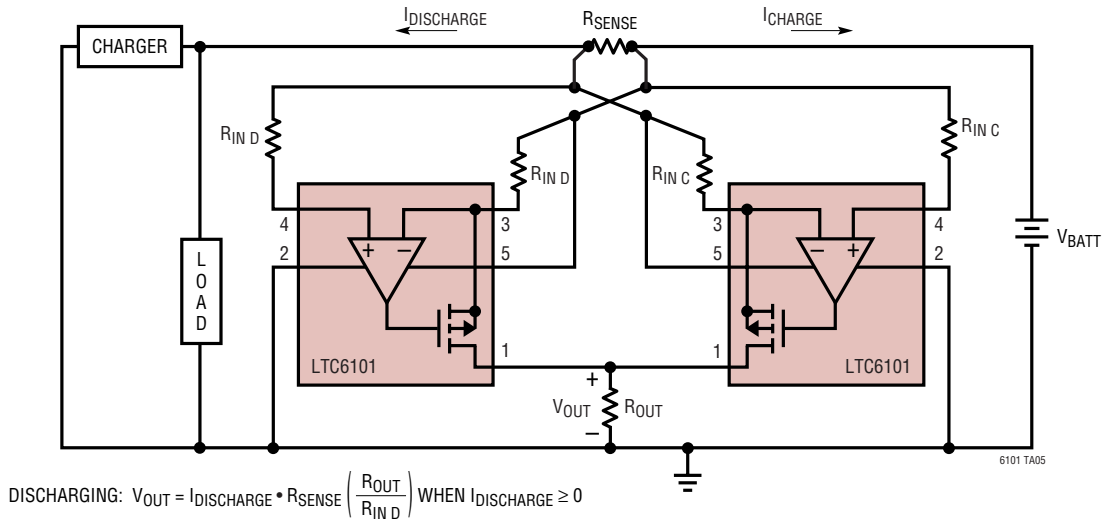


In this circuit the outputs are enabled by the direction of current flow. The battery current when either charging or discharging enables only one of the outputs. For example when charging, the $V_{OUT D}$ signal goes low since the output MOSFET of that LTC6101 turns completely off

while the other LTC6101, $V_{OUT C}$, ramps from low to high in proportion to the charging current. The active output reverses when the charger is removed and the battery discharges into the load.

APPLICATION NOTE 105: Current Sense Circuit Collection

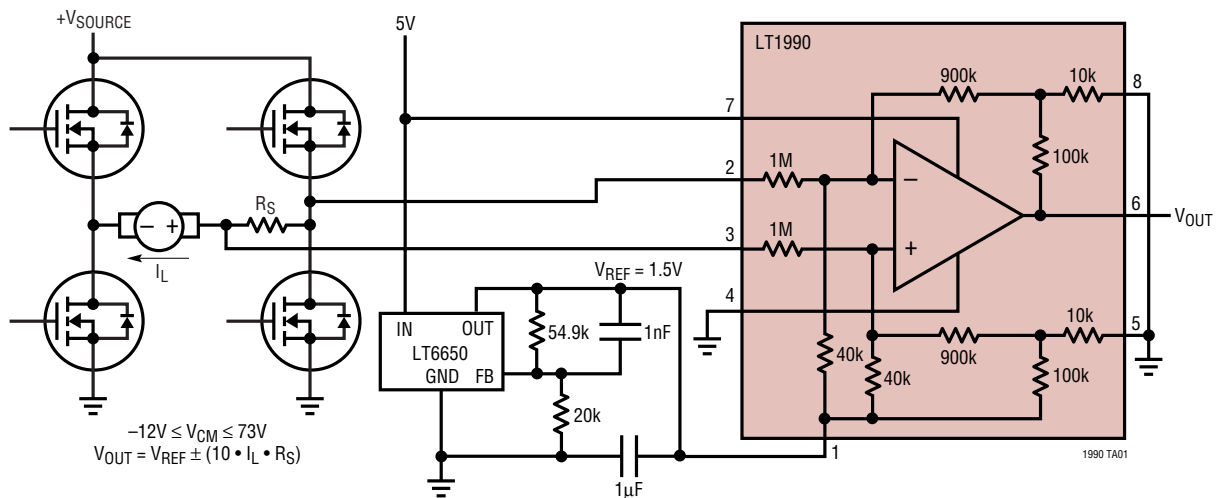
Bidirectional Absolute Value Current Sense



The high impedance current source outputs of two LTC6101's can be directly tied together. In this circuit the voltage at V_{OUT} continuously represents the absolute

value of the magnitude of the current into or out of the battery. The direction or polarity of the current flow is not discriminated.

Full-Bridge Load Current Monitor

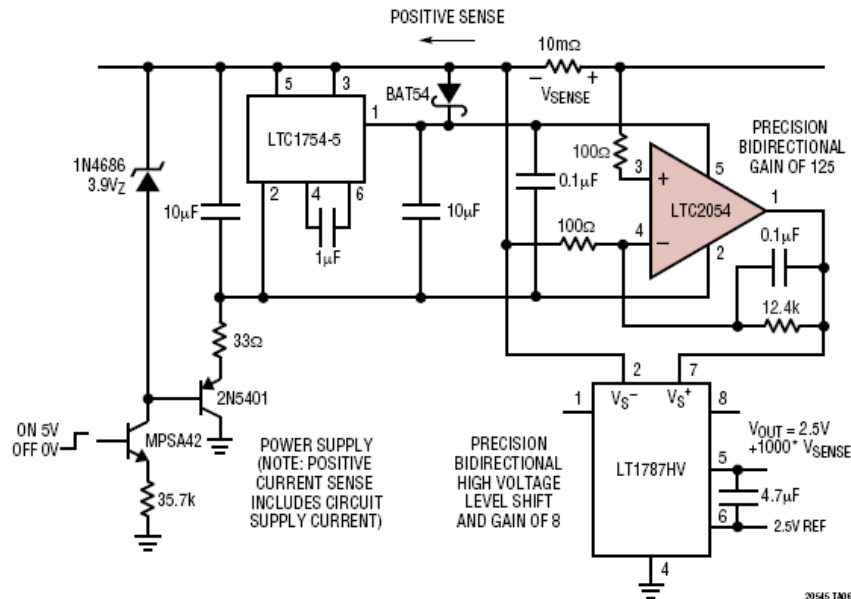


The LT1990 is a difference amplifier that features a very wide common mode input voltage range that can far exceed its own supply voltage. This is an advantage to reject transient voltages when used to monitor the current in a full bridge driven inductive load such as a motor. The LT6650 provides a voltage reference of 1.5V to bias up

the output away from ground. The output will move above or below 1.5V as a function of which direction the current in the load is flowing. As shown, the amplifier provides a gain of 10 to the voltage developed across resistor R_S .

APPLICATION NOTE 105: Current Sense Circuit Collection

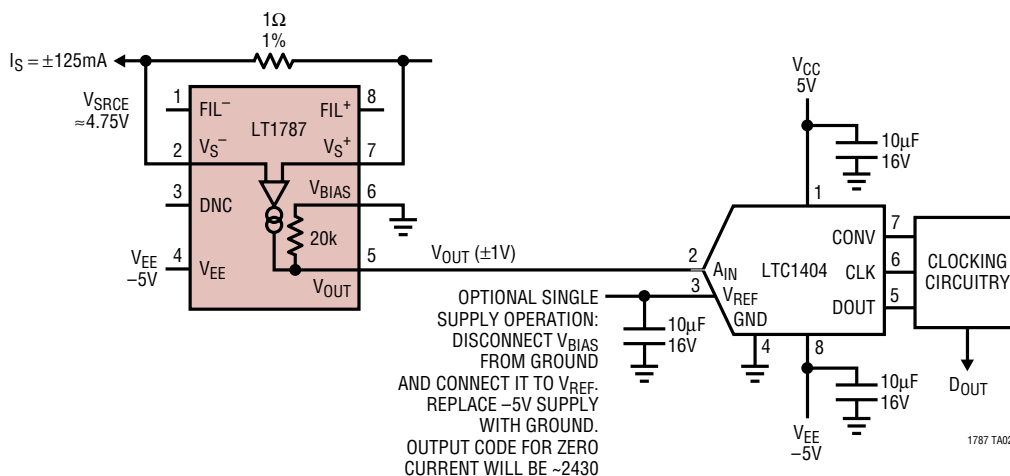
Low Power, Bidirectional 60V Precision Hi Side Current Sense



Using a very precise zero-drift amplifier as a pre-amp allows for the use of a very small sense resistor in a high voltage supply line. A floating power supply regulates the voltage across the pre-amplifier on any voltage rail up to

the 60V limit of the LT1787HV circuit. Overall gain of this circuit is 1000. A 1mA change in current in either direction through the 10mΩ sense resistor will produce a 10mV change in the output voltage.

Split or Single Supply Operation, Bidirectional Output into A/D



In this circuit, split supply operation is used on both the LT1787 and LTC1404 to provide a symmetric bidirectional measurement. In the single-supply case, where the

LT1787 pin 6 is driven by V_{REF} , the bidirectional measurement range is slightly asymmetric due to V_{REF} being somewhat greater than mid-span of the ADC input range.

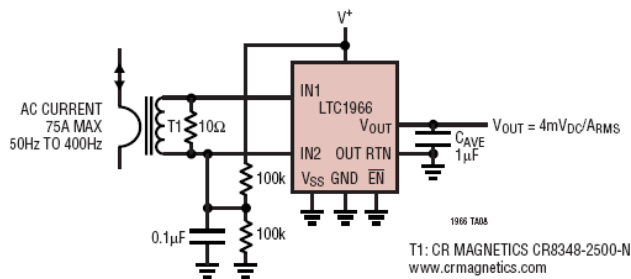
APPLICATION NOTE 105: Current Sense Circuit Collection

AC

Sensing current in ac power lines is quite tricky in the sense that both the current and voltage are continuously changing polarity. Transformer coupling of signals to drive ground referenced circuitry is often a good approach.

To see other chapters in this Application Note, return to the [Introduction](#).

Single Supply RMS Current Measurement



The LT1966 is a true RMS-to-DC converter that takes a single-ended or differential input signal with rail-to-rail range. The output of a pcb mounted current sense transformer can be connected directly to the converter. Up to 75A of AC current is measurable without breaking the signal path from a power source to a load. The accurate operating range of the circuit is determined by the selection of the transformer termination resistor. All of the math is built in to the LTC1966 to provide a dc output voltage that is proportional to the true rms value of the current. This is valuable in determining the power/energy consumption of ac powered appliances.

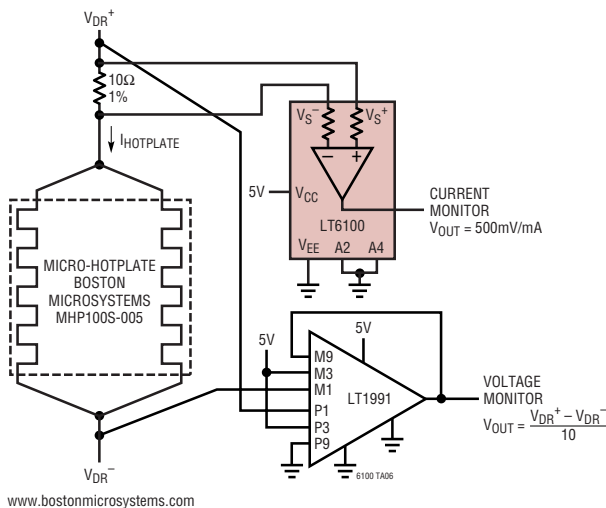
APPLICATION NOTE 105: Current Sense Circuit Collection

DC

DC current sensing is for measuring current flow that is changing at a very slow rate.

To see other chapters in this Application Note, return to the [Introduction](#).

Micro-Hotplate Voltage and Current Monitor

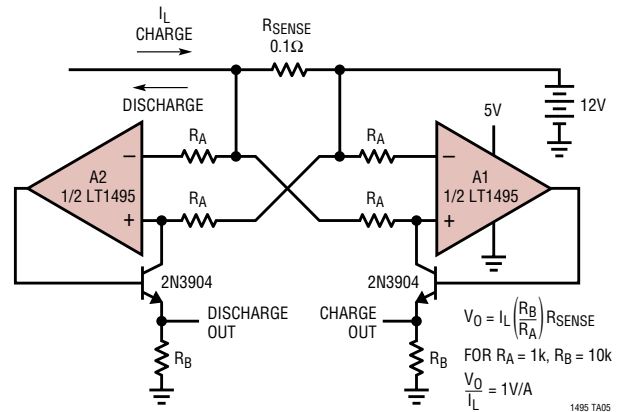


Materials science research examines the properties and interactions of materials at various temperatures. Some of the more interesting properties can be excited with localized nano-technology heaters and detected using the presence of interactive thin films.

While the exact methods of detection are highly complex and relatively proprietary, the method of creating localized heat is as old as the light bulb. Shown is the schematic of the heater elements of a Micro-hotplate from Boston Microsystems (www.bostonmicrosystems.com). The physical dimensions of the elements are tens of microns. They are micromachined out of SiC and heated with simple DC electrical power, being able to reach 1000°C without damage.

The power introduced to the elements, and thereby their temperature, is ascertained from the voltage-current product with the LT6100 measuring the current and the LT1991 measuring the voltage. The LT6100 senses the current by measuring the voltage across the 10Ω resistor, applies a gain of 50, and provides a ground referenced output. The I to V gain is therefore 500mV/mA, which makes sense given the 10mA full scale heater current and the 5V output swing of the LT6100. The LT1991's task is the opposite, applying precision attenuation instead of gain. The full scale voltage of the heater is a total of 40V (±20), beyond which the life of the heater may be reduced in some atmospheres. The LT1991 is set up for an attenuation factor of 10, so that the 40V full scale differential drive becomes 4V ground referenced at the LT1991 output. In both cases, the voltages are easily read by 0V–5V PC I/O cards and the system readily software controlled.

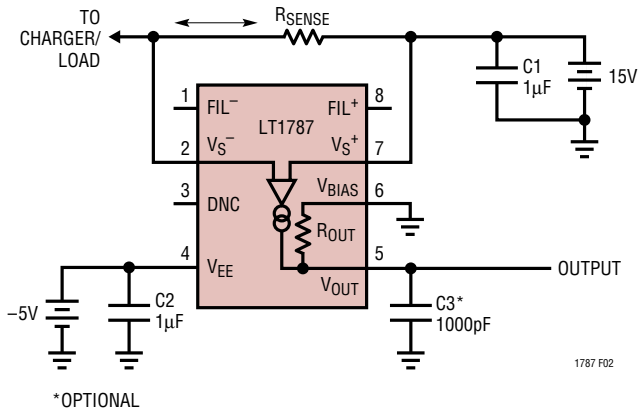
Battery Current Monitor



One LT1495 dual op-amp package can be used to establish separate charge and discharge current monitoring outputs. The LT1495 features Over-the-Top operation allowing the battery potential to be as high as 36V with only a 5V amplifier supply voltage.

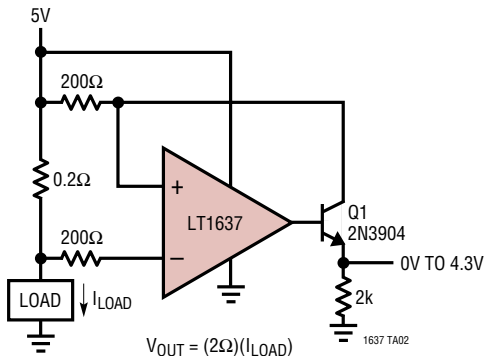
APPLICATION NOTE 105: Current Sense Circuit Collection

Bidirectional Battery-Current Monitor



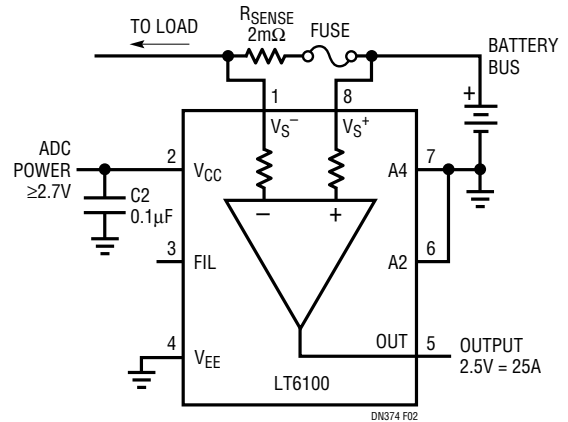
This circuit provides the capability of monitoring current in either direction through the sense resistor. To allow negative outputs to represent charging current, V_{EE} is connected to a small negative supply. In single-supply operation (V_{EE} at ground), the output range may be offset upwards by applying a positive reference level to V_{BIAS} (1.25V for example). $C3$ may be used to form a filter in conjunction with the output resistance (R_{OUT}) of the part. This solution offers excellent precision (very low V_{OS}) and a fixed nominal gain of 8.

“Classic” Positive Supply Rail Current Sense



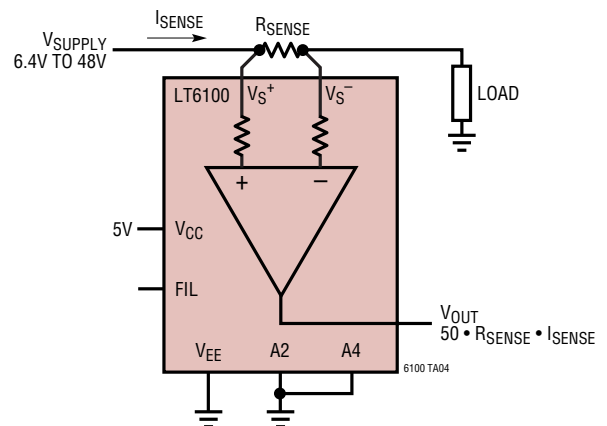
This circuit uses generic devices to assemble a function similar to an LTC6101. A Rail-to-Rail Input type op amp is required since input voltages are right at the upper rail. The circuit shown here is capable of monitoring up to 44V applications. Besides the complication of extra parts, the V_{OS} performance of op amps at the supply is generally not factory trimmed, thus less accurate than other solutions. The finite current gain of the bipolar transistor is a small source of gain error.

High Side Current Sense and Fuse Monitor



The LT6100 can be used as a combination current sensor and fuse monitor. This part includes on-chip output buffering and was designed to operate with the low supply voltage ($\geq 2.7V$), typical of vehicle data acquisition systems, while the sense inputs monitor signals at the higher battery bus potential. The LT6100 inputs are tolerant of large input differentials, thus allowing the blown-fuse operating condition (this would be detected by an output full-scale indication). The LT6100 can also be powered down while maintaining high impedance sense inputs, drawing less than $1\mu A$ max from the battery bus.

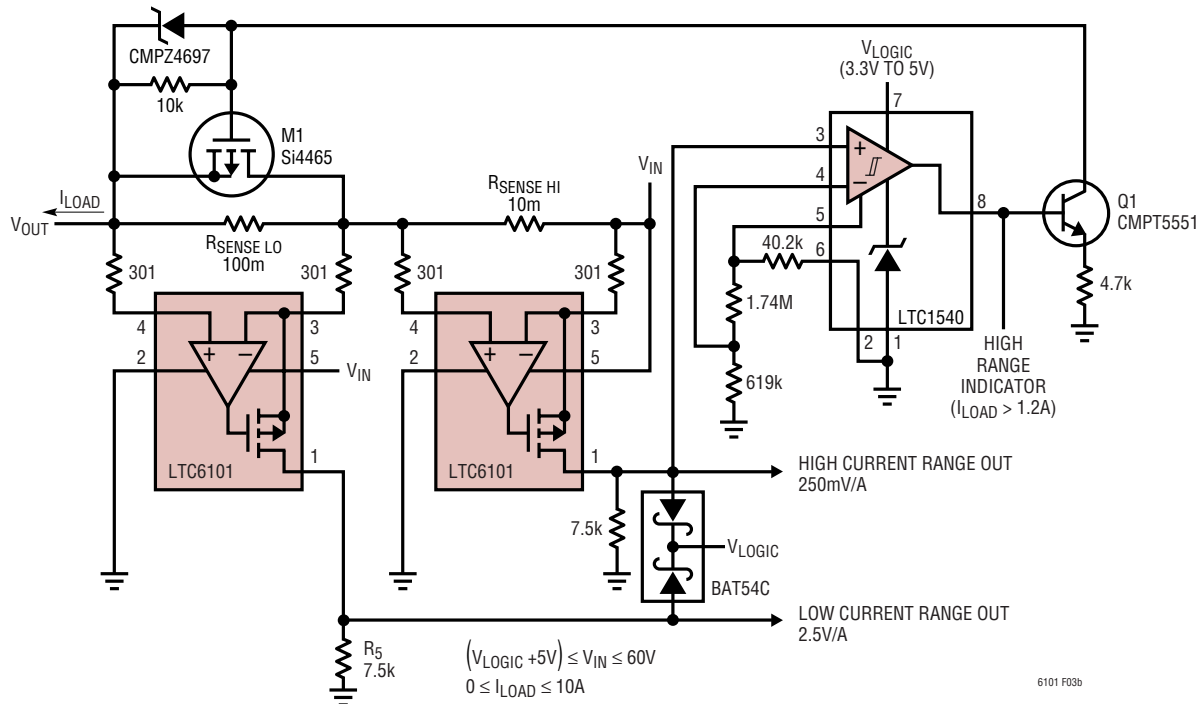
Gain of 50 Current Sense



The LT6100 is configured for a gain of 50 by grounding both A2 and A4. This is one of the simplest current sensing amplifier circuits where only a sense resistor is required.

APPLICATION NOTE 105: Current Sense Circuit Collection

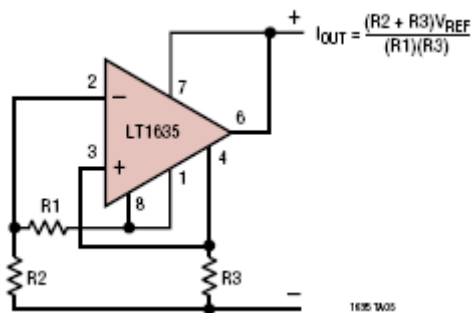
Dual LTC6101's Allow High-Low Current Ranging



Using two current sense amplifiers with two values of sense resistors is an easy method of sensing current over a wide range. In this circuit the sensitivity and resolution of measurement is 10 times greater with low cur-

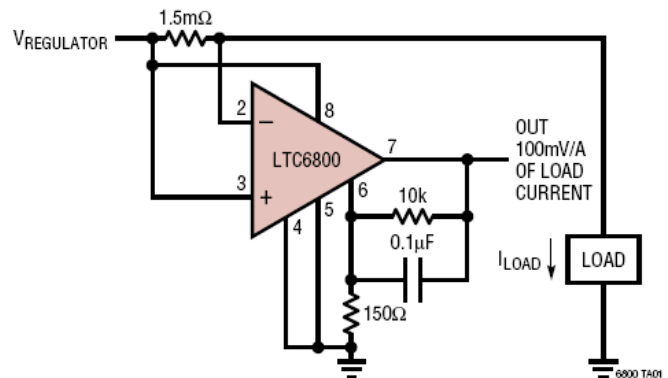
rents, less than 1.2 Amps, than with higher currents. A comparator detects higher current flow, up to 10 Amps, and switches sensing over to the high current circuitry.

Two Terminal Current Regulator



The LT1635 combines an op amp with a 200mV reference. Scaling this reference voltage to a potential across resistor R3 forces a controlled amount of current to flow from the +terminal to the -terminal. Power is taken from the loop.

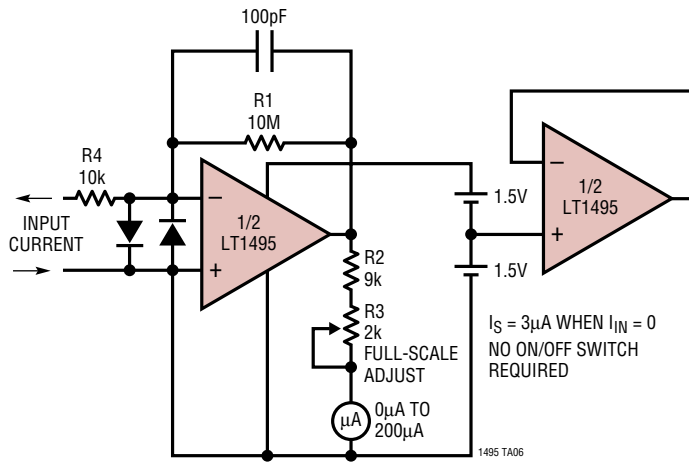
High Side Power Supply Current Sense



The low offset error of the LTC6800 allows for unusually low sense resistance while retaining accuracy.

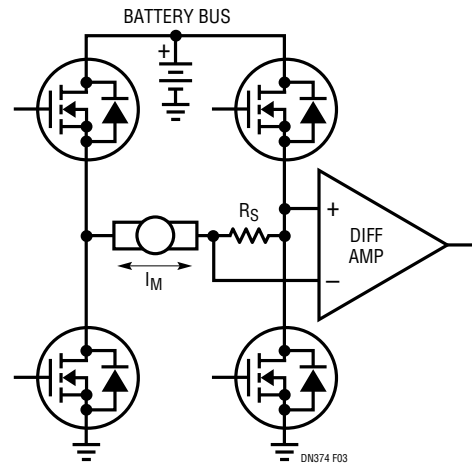
APPLICATION NOTE 105: Current Sense Circuit Collection

0nA to 200nA Current Meter



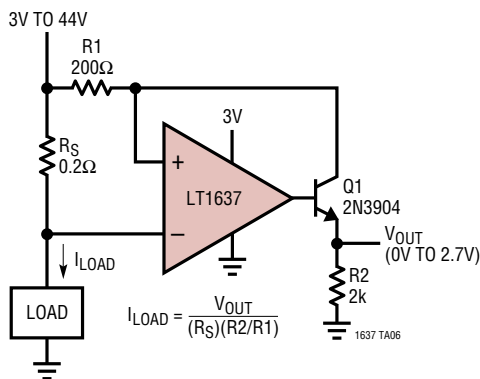
A floating amplifier circuit converts a full-scale 200nA flowing in the direction indicated at the inputs to 2V at the output of the LT1495. This voltage is converted to a current to drive a 200μA meter movement. By floating the power to the circuit with batteries, any voltage potential at the inputs are handled. The LT1495 is a micro-power op amp so the quiescent current drain from the batteries is very low and thus no on/off switch is required.

Conventional H-Bridge Current Monitor



Many of the newer electric drive functions, such as steering assist, are bidirectional in nature. These functions are generally driven by H-bridge MOSFET arrays using pulse-width-modulation (PWM) methods to vary the commanded torque. In these systems, there are two main purposes for current monitoring. One is to monitor the current in the load, to track its performance against the desired command (i.e., closed-loop servo law), and another is for fault detection and protection features.

Over-The-Top Current Sense

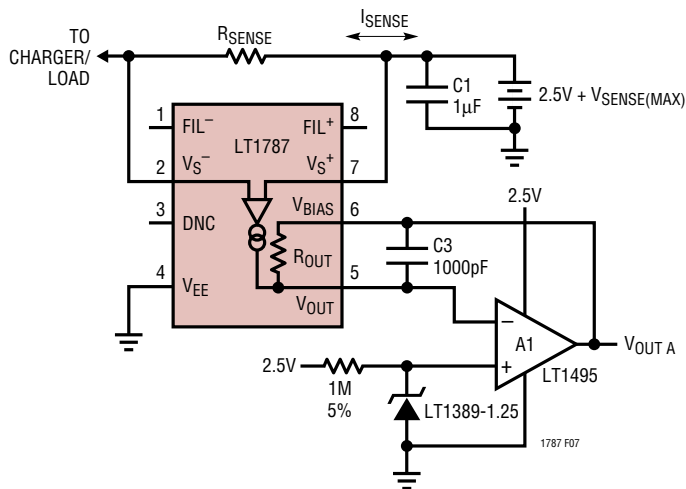


This circuit is a variation on the “classic” high-side circuit, but takes advantage of Over-the-Top input capability to separately supply the IC from a low-voltage rail. This provides a measure of fault protection to downstream circuitry by virtue of the limited output swing set by the low-voltage supply. The disadvantage is V_{OS} in the Over-the-Top mode is generally inferior to other modes, thus less accurate. The finite current gain of the bipolar transistor is a source of small gain error.

A common monitoring approach in these systems is to amplify the voltage on a “flying” sense resistor, as shown. Unfortunately, several potentially hazardous fault scenarios go undetected, such as a simple short to ground at a motor terminal. Another complication is the noise introduced by the PWM activity. While the PWM noise may be filtered for purposes of the servo law, information useful for protection becomes obscured. The best solution is to simply provide two circuits that individually protect each half-bridge and report the bidirectional load current. In some cases, a smart MOSFET bridge driver may already include sense resistors and offer the protection features needed. In these situations, the best solution is the one that derives the load information with the least additional circuitry.

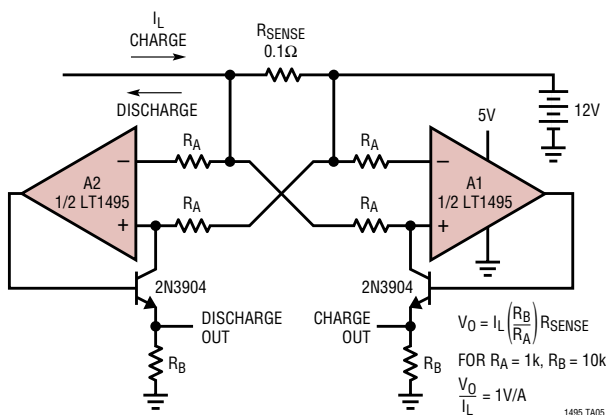
APPLICATION NOTE 105: Current Sense Circuit Collection

Single Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter



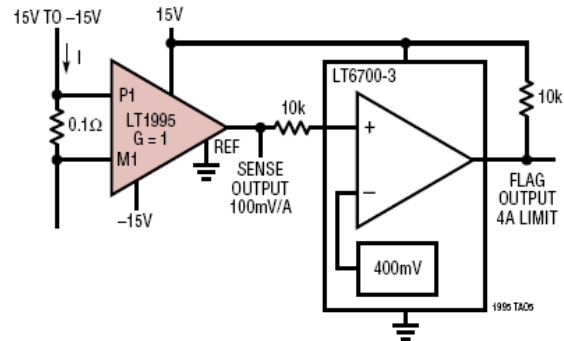
The LT1787's output is buffered by an LT1495 rail-to-rail op-amp configured as an I/V converter. This configuration is ideal for monitoring very low voltage supplies. The LT1787's V_{OUT} pin is held equal to the reference voltage appearing at the op amp's non-inverting input. This allows one to monitor supply voltages as low as 2.5V. The op-amp's output may swing from ground to its positive supply voltage. The low impedance output of the op amp may drive following circuitry more effectively than the high output impedance of the LT1787. The I/V converter configuration also works well with split supply voltages.

Battery Current Monitor



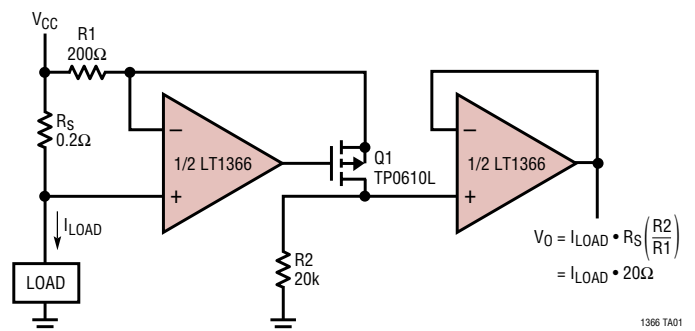
One LT1495 dual op-amp package can be used to establish separate charge and discharge current monitoring outputs. The LT1495 features Over-the-Top operation allowing the battery potential to be as high as 36V with only a 5V amplifier supply voltage.

Fast Current Sense with Alarm



The LT1995 is shown as a simple unity gain difference amplifier. When biased with split supplies the input current can flow in either direction providing an output voltage of 100mV per Amp from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/usec slew rate the response of this sense amplifier is fast. Adding a simple comparator with a built in reference voltage circuit such as the LT6700-3 can be used to generate an over-current flag. With the 400mV reference the flag occurs at 4A.

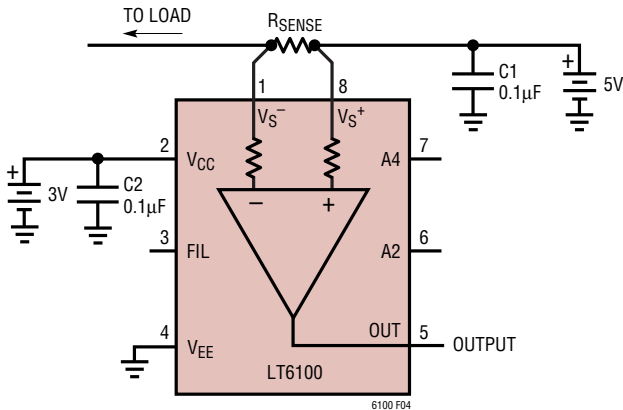
Positive Supply Rail Current Sense



This is a configuration similar to an LT6100 implemented with generic components. A Rail-to-Rail or Over-the-Top input op amp type is required (for the first section). The first section is a variation on the classic high-side where the P-MOSFET provides an accurate output current into R_2 (compared to a BJT). The second section is a buffer to allow driving ADC ports, etc., and could be configured with gain if needed. As shown, this circuit can handle up to 36V operation. Small-signal range is limited by V_{OL} in single-supply operation.

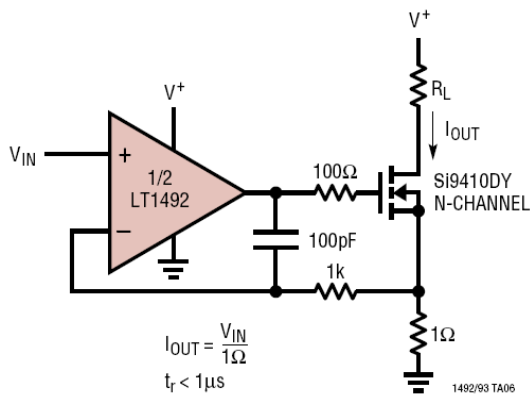
APPLICATION NOTE 105: Current Sense Circuit Collection

LT6100 Load Current Monitor



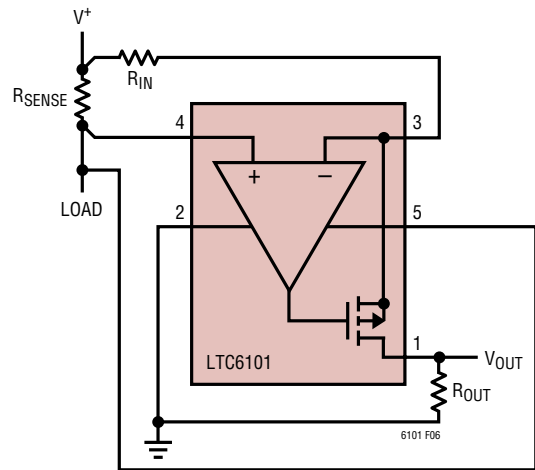
This is the basic LT6100 circuit configuration. The internal circuitry, including an output buffer, typically operates from a low voltage supply, such as the 3V shown. The monitored supply can range anywhere from $V_{CC} + 1.4V$ up to 48V. The A2 and A4 pins can be strapped various ways to provide a wide range of internally fixed gains. The input leads become very hi-Z when V_{CC} is powered down, so as not to drain batteries for example. Access to an internal signal node (pin 3) provides an option to include a filtering function with one added capacitor. Small-signal range is limited by V_{OL} in single-supply operation.

1A Voltage-Controlled Current Sink



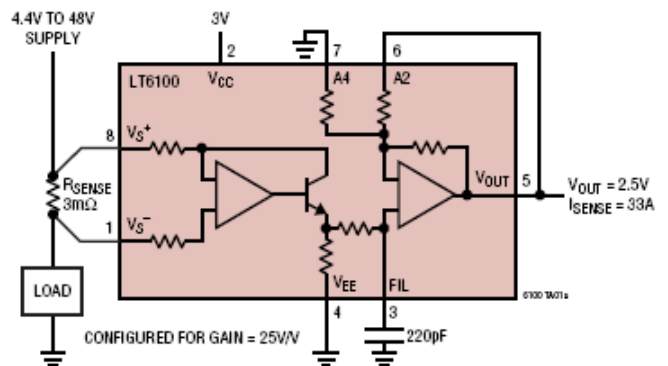
This is a simple controlled current sink, where the op amp drives the NMOSFET gate to develop a match between the 1Ω sense resistor drop and the V_{IN} current command. Since the common-mode voltage seen by the op amp is near ground potential, a “single-supply” or Rail-to-Rail type is required in this application.

LTC6101 Supply Current included as Load in Measurement



This is the basic LTC6101 high-side sensing supply-monitor configuration, where the supply current drawn by the IC is included in the readout signal. This configuration is useful when the IC current may not be negligible in terms of overall current draw, such as in low-power battery-powered applications. R_{SENSE} should be selected to limit voltage-drop to <500mV for best linearity. If it is desirable not to include the IC current in the readout, as in load monitoring, pin 5 may be connected directly to V^+ instead of the load. Gain accuracy of this circuit is limited only by the precision of the resistors selected by the user.

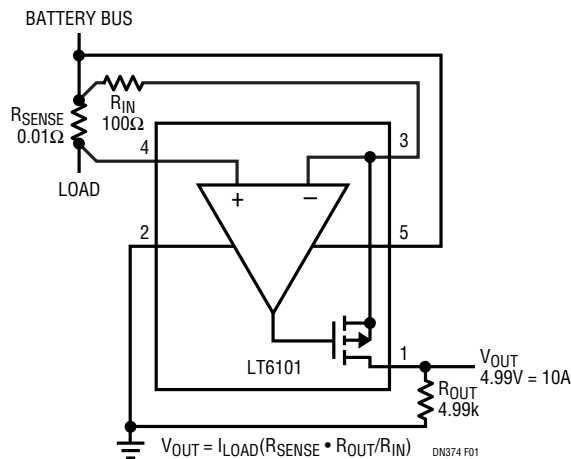
V+ Powered Separately from Load Supply



The inputs of the LTC6101 can function from 1.4V above the device positive supply to 48V DC. In this circuit the current flow in the high voltage rail is directly translated to a 0V to 3V range.

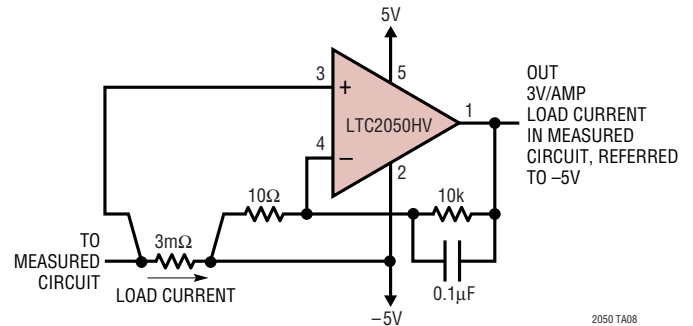
APPLICATION NOTE 105: Current Sense Circuit Collection

Simple High Side Current Sense Using the LTC6101



This is a basic high side current monitor using the LTC6101. The selection of R_{IN} and R_{OUT} establishes the desired gain of this circuit, powered directly from the battery bus. The current output of the LTC6101 allows it to be located remotely to R_{OUT} . Thus, the amplifier can be placed directly at the shunt, while R_{OUT} is placed near the monitoring electronics without ground drop errors. This circuit has a fast $1\mu s$ response time that makes it ideal for providing MOSFET load switch protection. The switch element may be the high side type connected between the sense resistor and the load, a low side type between the load and ground or an H-bridge. The circuit is programmable to produce up to 1mA of full-scale output current into R_{OUT} , yet draws a mere $250\mu A$ supply current when the load is off.

“Classic” High-Precision Low Side Current Sense



This configuration is basically a standard non-inverting amplifier. The op amp used must support common-mode operation at the lower rail and the use of a Zero-Drift type (as shown) provides excellent precision. The output of this circuit is referenced to the lower Kelvin contact, which could be ground in a single-supply application. Small-signal range is limited by V_{OL} for single-supply designs. Scaling accuracy is set by the quality of the user-selected resistors.

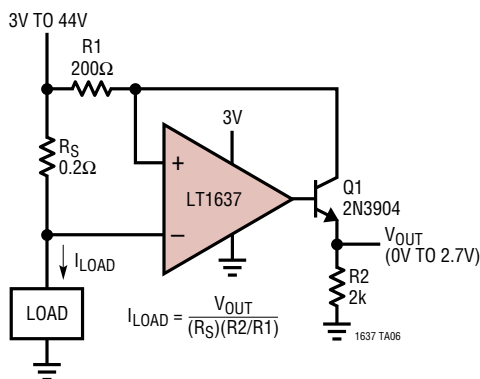
APPLICATION NOTE 105: Current Sense Circuit Collection

Level Shifting

Quite often it is required to sense current flow in a supply rail that is a much higher voltage potential than the supply voltage for the system electronics. Current sense circuits with high voltage capability are useful to translate information to lower voltage signals for processing.

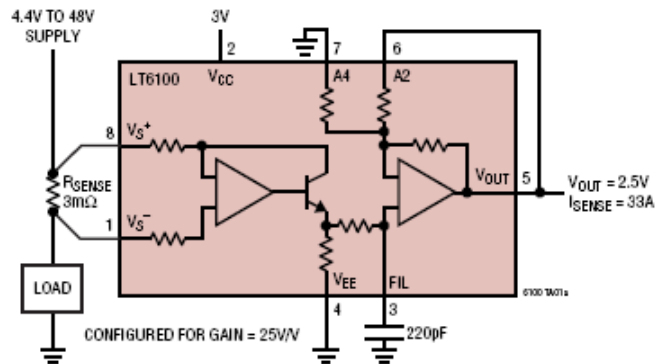
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Over-The-Top Current Sense



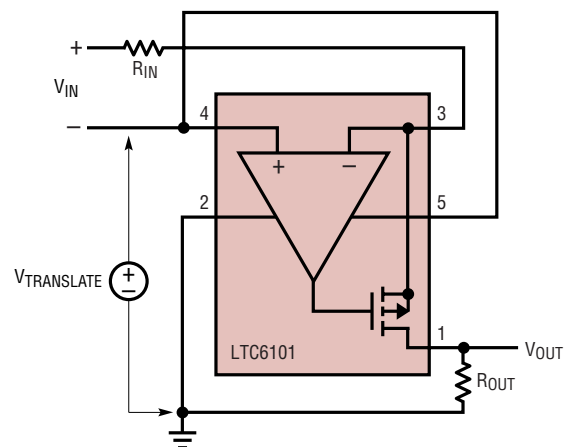
This circuit is a variation on the “classic” high-side circuit, but takes advantage of Over-the-Top input capability to separately supply the IC from a low-voltage rail. This provides a measure of fault protection to downstream circuitry by virtue of the limited output swing set by the low-voltage supply. The disadvantage is V_{OS} in the Over-the-Top mode is generally inferior to other modes, thus less accurate. The finite current gain of the bipolar transistor is a source of small gain error.

V+ Powered Separately from Load Supply



The inputs of the LTC6101 can function from 1.4V above the device positive supply to 48V DC. In this circuit the current flow in the high voltage rail is directly translated to a 0V to 3V range.

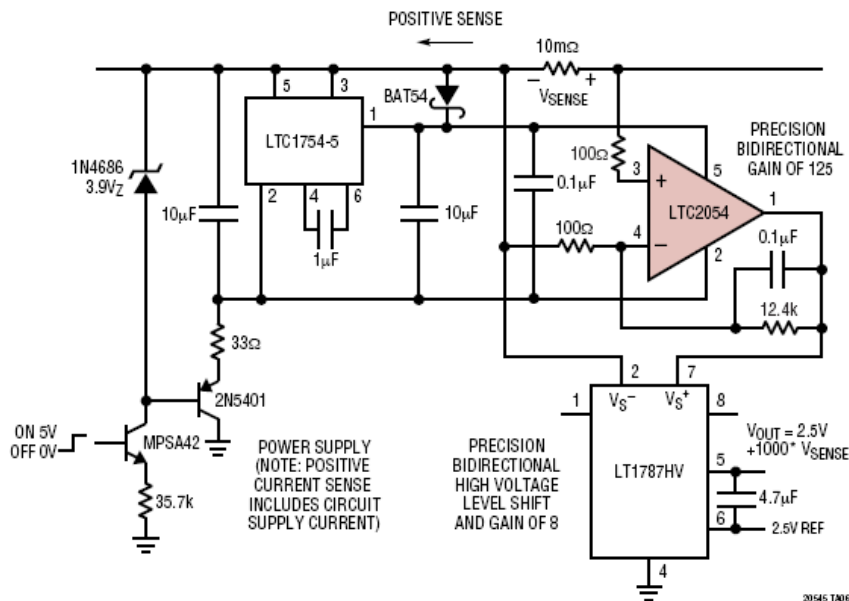
Voltage Translator



This is a convenient usage of the LTC6101 current sense amplifier as a high voltage level translator. Differential voltage signals riding on top of a high common mode voltage (up to 105V with the LTC6101HV) get converted to a current, through R_{IN} , and then scaled down to a ground referenced voltage across R_{OUT} .

APPLICATION NOTE 105: Current Sense Circuit Collection

Low Power, Bidirectional 60V Precision Hi Side Current Sense



Using a very precise zero-drift amplifier as a pre-amp allows for the use of a very small sense resistor in a high voltage supply line. A floating power supply regulates the voltage across the pre-amplifier on any voltage rail up to

the 60V limit of the LT1787HV circuit. Overall gain of this circuit is 1000. A 1mA change in current in either direction through the 10mΩ sense resistor will produce a 10mV change in the output voltage.

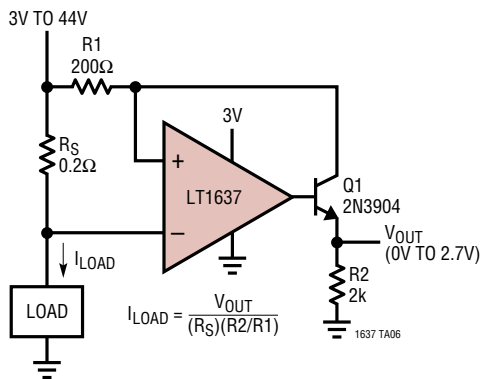
APPLICATION NOTE 105: Current Sense Circuit Collection

High Voltage

Monitoring current flow in a high voltage line often requires floating the supply of the measuring circuits up near the high voltage potentials. Level shifting and isolation components are then often used to develop a lower output voltage indication.

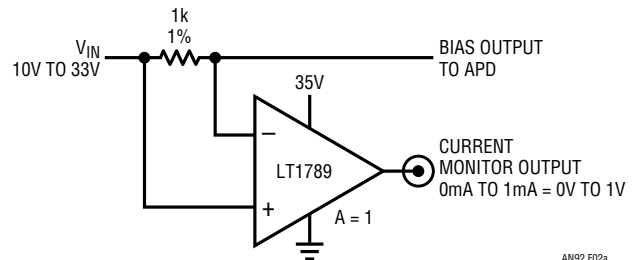
To see other chapters in this Application Note, return to the [Introduction](#).

Over-The-Top Current Sense

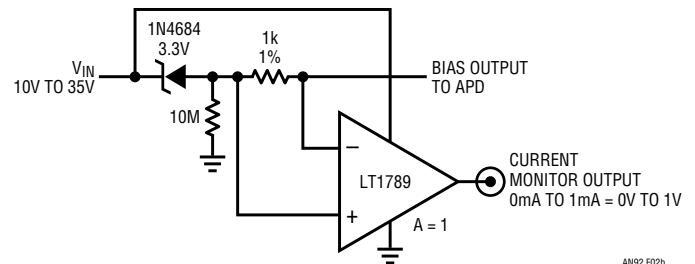


This circuit is a variation on the “classic” high-side circuit, but takes advantage of Over-the-Top input capability to separately supply the IC from a low-voltage rail. This provides a measure of fault protection to downstream circuitry by virtue of the limited output swing set by the low-voltage supply. The disadvantage is V_{OS} in the Over-the-Top mode is generally inferior to other modes, thus less accurate. The finite current gain of the bipolar transistor is a source of small gain error.

Measuring bias current into an Avalanche Photo Diode (APD) using an instrumentation amplifier.



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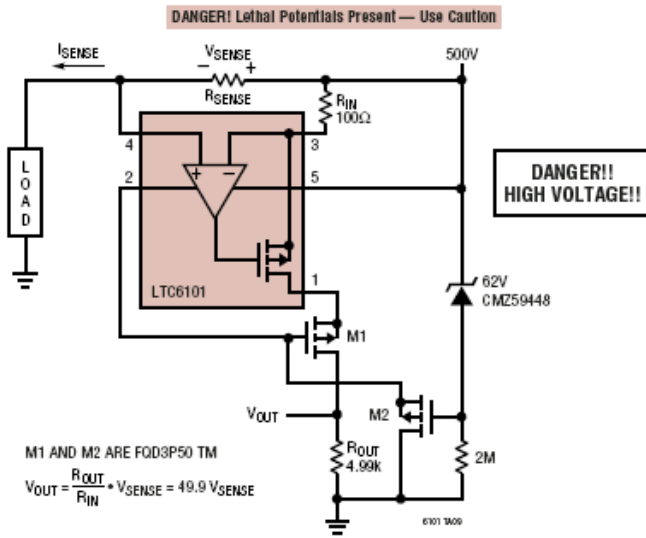


AN92 F02b

The upper circuit uses an instrumentation amplifier (IA) powered by a separate rail (>1V above V_{IN}) to measure across the 1kΩ current shunt. The lower figure is similar but derives its power supply from the APD bias line. The limitation of these circuits is the 35V maximum APD voltage, whereas some APDs may require 90V or more. In the single-supply configuration shown, there is also a dynamic range limitation due to V_{OL} to consider. The advantage of this approach is the high accuracy that is available in an IA.

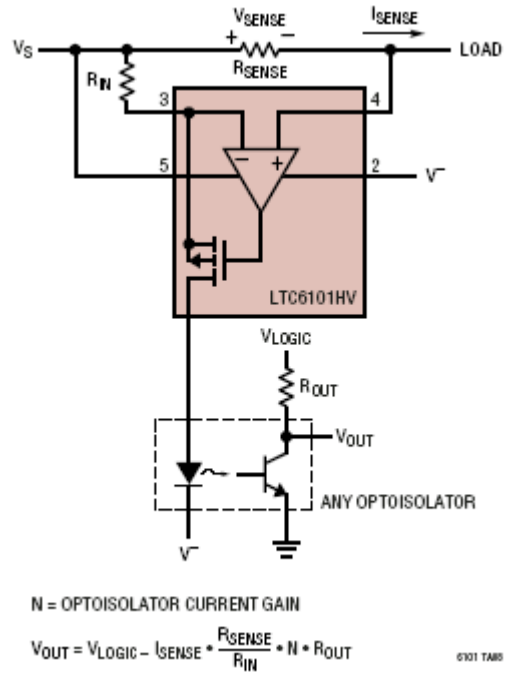
APPLICATION NOTE 105: Current Sense Circuit Collection

Simple 500V Current Monitor



Adding two external Mosfets to hold off the voltage allows the LTC6101 to connect to very high potentials and monitor the current flow. The output current from the LTC6101, which is proportional to the sensed input voltage, flows through M1 to create a ground referenced output voltage.

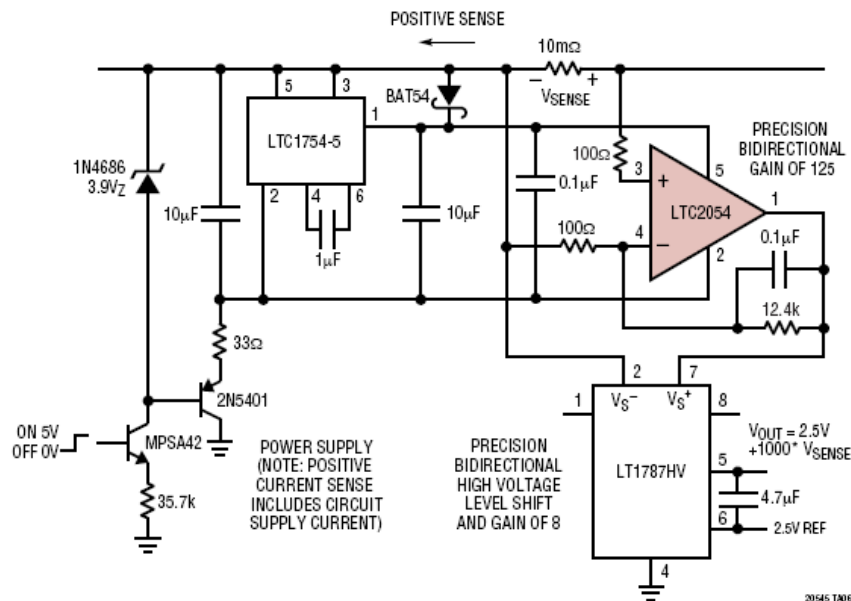
48V Supply Current Monitor with Isolated Output and 105V Survivability



The HV version of the LTC6101 can operate with a total supply voltage of 105V. Current flow in high supply voltage rails can be monitored directly or in an isolated fashion as shown in this circuit. The gain of the circuit and the level of output current from the LTC6101 depends on the particular opto-isolator used.

APPLICATION NOTE 105: Current Sense Circuit Collection

Low Power, Bidirectional 60V Precision Hi Side Current Sense



Using a very precise zero-drift amplifier as a pre-amp allows for the use of a very small sense resistor in a high voltage supply line. A floating power supply regulates the voltage across the pre-amplifier on any voltage rail up to

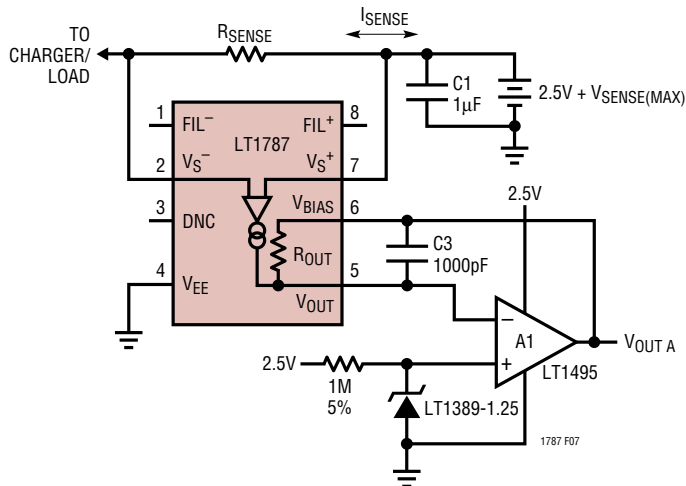
the 60V limit of the LT1787HV circuit. Overall gain of this circuit is 1000. A 1mA change in current in either direction through the 10mΩ sense resistor will produce a 10mV change in the output voltage.

APPLICATION NOTE 105: Current Sense Circuit Collection

Low Voltage

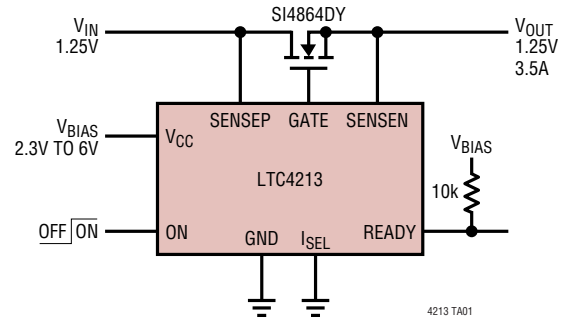
To see other chapters in this Application Note, return to the [Introduction](#).

Single Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter



The LT1787's output is buffered by an LT1495 rail-to-rail op-amp configured as an I/V converter. This configuration is ideal for monitoring very low voltage supplies. The LT1787's V_{OUT} pin is held equal to the reference voltage appearing at the op amp's non-inverting input. This allows one to monitor supply voltages as low as 2.5V. The op-amp's output may swing from ground to its positive supply voltage. The low impedance output of the op amp may drive following circuitry more effectively than the high output impedance of the LT1787. The I/V converter configuration also works well with split supply voltages.

1.25V Electronic Circuit Breaker



The LTC4213 provides protection and automatic circuit breaker action by sensing Drain-to-Source voltage-drop across the NMOSFET. The sense inputs have a Rail-to-Rail common mode range, so the circuit breaker can protect bus voltages from 0V up to 6V. Logic signals flag a trip condition (with the READY output signal) and reinitialize the breaker (using the ON input). The ON input may also be used as a command in a “smart switch” application.

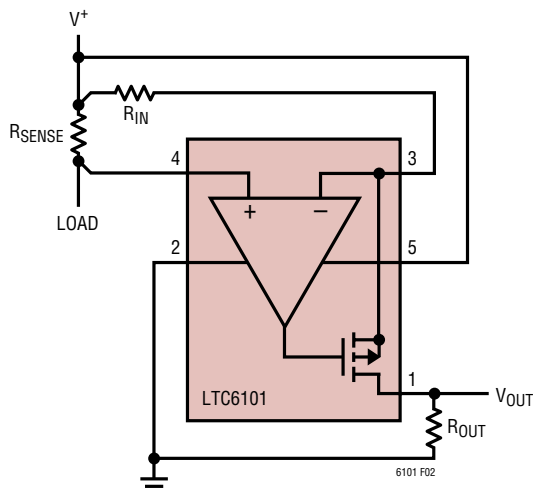
APPLICATION NOTE 105: Current Sense Circuit Collection

High Current (100mA to Amps)

Sensing high currents accurately requires excellent control of the sensing resistance, which is typically a very small value to minimize losses, and the dynamic range of the measurement circuitry

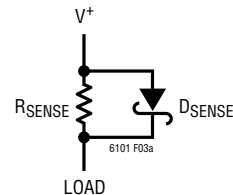
To see other chapters in this Application Note, return to the [Introduction](#).

Kelvin Input Connection Preserves Accuracy Despite Large Load Currents



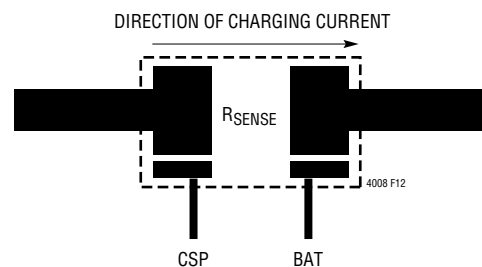
Kelvin connection of the IN- and IN+ inputs to the sense resistor should be used in all but the lowest power applications. Solder connections and PC board interconnections that carry high current can cause significant error in measurement due to their relatively large resistances. By isolating the sense traces from the high current paths, this error can be reduced by orders of magnitude. A sense resistor with integrated Kelvin sense terminals will give the best results.

Shunt Diode Limits Maximum Input Voltage to Allow Better Low Input Resolution Without Over-Ranging the LTC6101



If low sense currents must be resolved accurately in a system that has very wide dynamic range, more gain can be taken in the sense amplifier by using a smaller value for resistor R_{IN} . This can result in an operating current greater than the max current spec allowed unless the max current is limited in another way, such as with a Schottky diode across R_{SENSE} . This will reduce the high current measurement accuracy by limiting the result, while increasing the low current measurement resolution. This approach can be helpful in cases where an occasional large burst of current may be ignored.

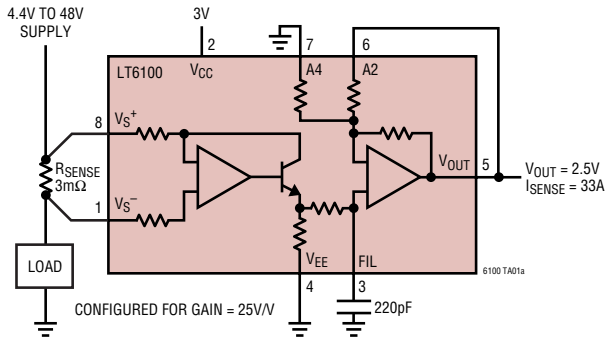
Kelvin Sensing



In any high current, >1Amp, application, Kelvin contacts to the sense resistor are important to maintain accuracy. This simple illustration from a battery charger application shows two voltage-sensing traces added to the pads of the current sense resistor. If the voltage is sensed with high impedance amplifier inputs, no $I \times R$ voltage drop errors are developed.

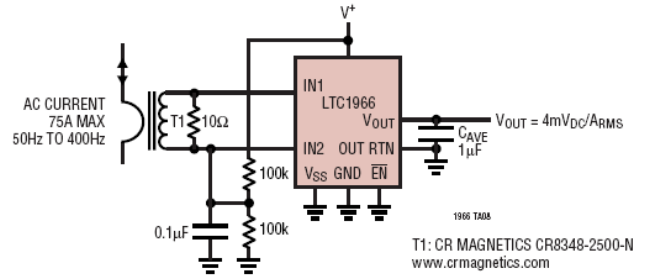
APPLICATION NOTE 105: Current Sense Circuit Collection

0A to 33A High Side Current Monitor with Filtering



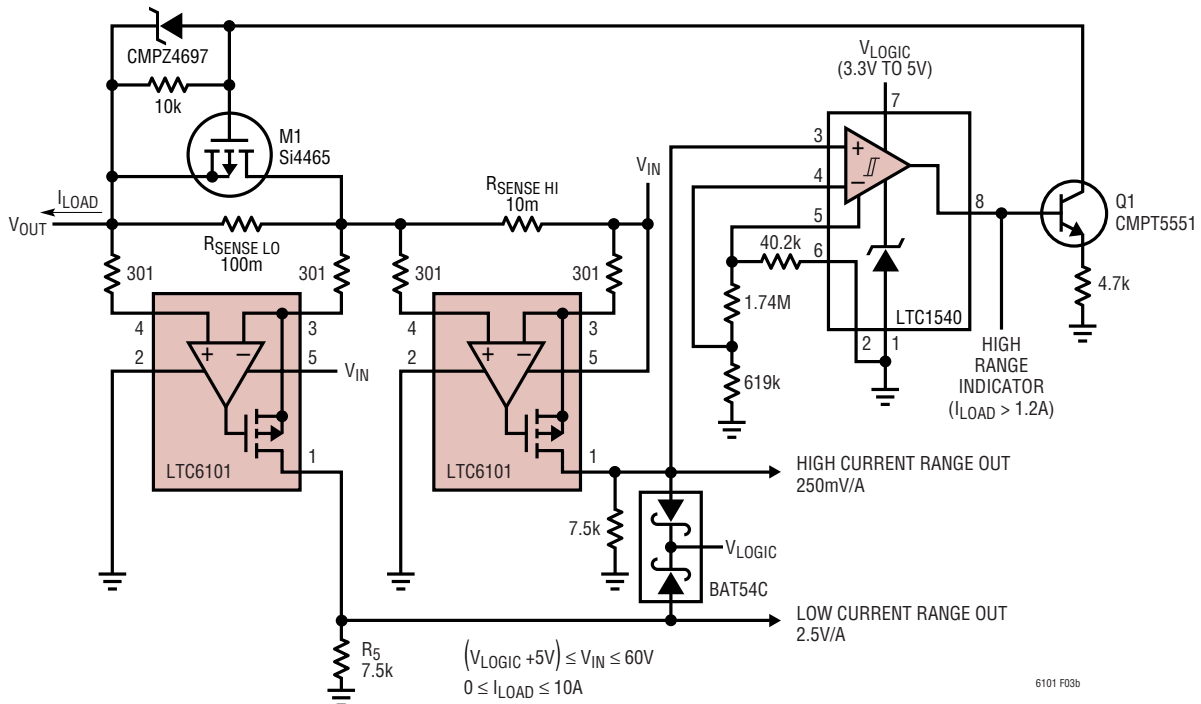
High current sensing on a high voltage supply rail is easily accomplished with the LT6100. The sense amplifier is biased from a low 3V supply and pin-strapped to a gain of 25V/V to output a 2.5V full scale reading of the current flow. A capacitor at the FIL pin to ground will filter out noise of the system (220pF produces a 12KHz low pass corner frequency).

Single Supply RMS Current Measurement



The LTC1966 is a true RMS-to-DC converter that takes a single-ended or differential input signal with rail-to-rail range. The output of a pcb mounted current sense transformer can be connected directly to the converter. Up to 75A of AC current is measurable without breaking the signal path from a power source to a load. The accurate operating range of the circuit is determined by the selection of the transformer termination resistor. All of the math is built in to the LTC1966 to provide a dc output voltage that is proportional to the true rms value of the current. This is valuable in determining the power/energy consumption of ac powered appliances.

Dual LTC6101's Allow High-Low Current Ranging

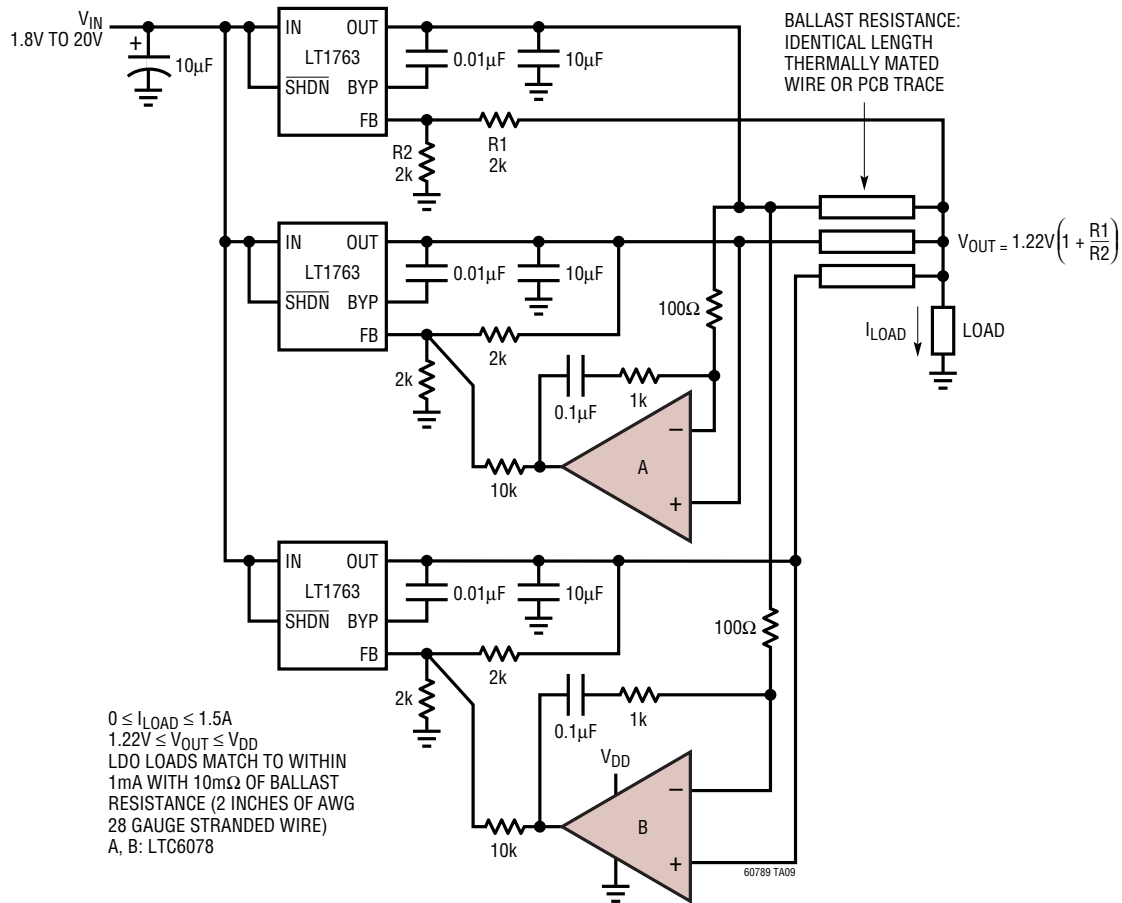


APPLICATION NOTE 105: Current Sense Circuit Collection

Using two current sense amplifiers with two values of sense resistors is an easy method of sensing current over a wide range. In this circuit the sensitivity and resolution of measurement is 10 times greater with low cur-

rents, less than 1.2 Amps, than with higher currents. A comparator detects higher current flow, up to 10 Amps, and switches sensing over to the high current circuitry.

LDO Load Balancing

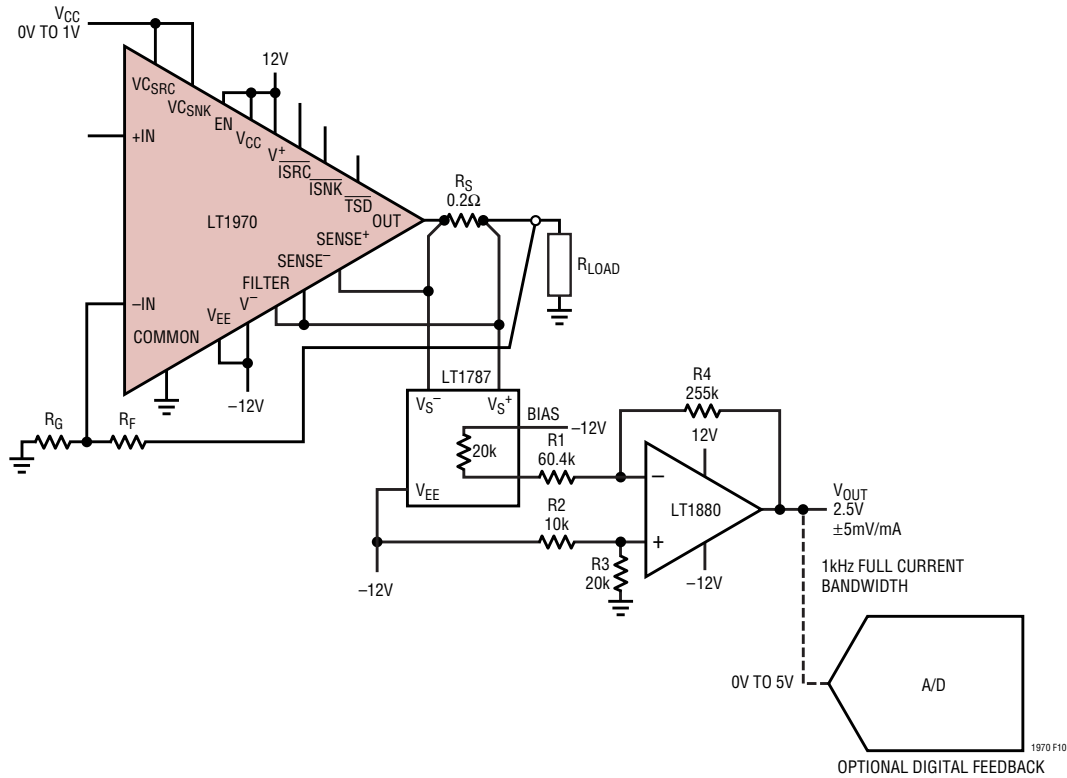


As system design enhancements are made there is often the need to supply more current to a load than originally expected. A simple way to modify power amplifiers or voltage regulators, as shown here, is to parallel devices. When paralleling devices it is desired that each device shares the total load current equally. In this circuit two adjustable “slave” regulator output voltages are sensed

and servo'd to match the master regulator output voltage. The precise low offset voltage of the LTC6078 dual op amp (10uV) balances the load current provided by each regulator to within 1mA. This is achieved using a very small 10mΩ current sense resistor in series with each output. This sense resistor can be implemented with pcb copper traces or thin gauge wire.

APPLICATION NOTE 105: Current Sense Circuit Collection

Sensing Output Current



The LT1970 is a 500mA power amplifier with voltage programmable output current limit. Separate DC voltage inputs and an output current sensing resistor control the maximum sourcing and sinking current values. These control voltages could be provided by a D-to-A Converter

in a microprocessor controlled system. For closed loop control of the current to a load an LT1787 can monitor the output current. The LT1880 op amp provides scaling and level shifting of the voltage applied to an A-to-D Converter for a 5mV/mA feedback signal.

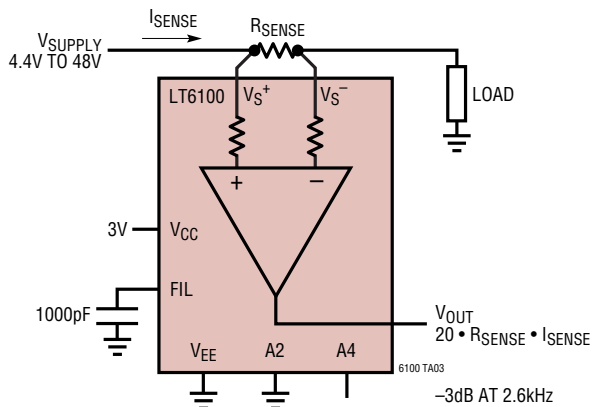
APPLICATION NOTE 105: Current Sense Circuit Collection

Low Current (Picoamps to Milliamps)

For low current applications the easiest way to sense current is to use a large sense resistor. This however causes larger voltage drops in the line being sensed which may not be acceptable. Using a smaller sense resistor and taking gain in the sense amplifier stage is often a better approach. Low current implies high source impedance measurements which are subject to noise pickup and often require filtering of some sort.

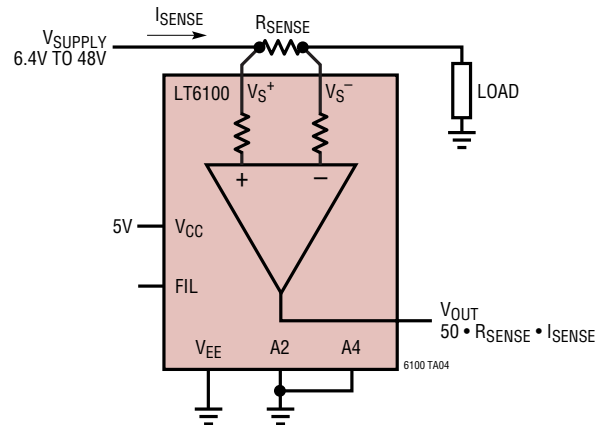
To see other chapters in this Application Note, return to the [Introduction](#).

Filtered Gain of 20 Current Sense



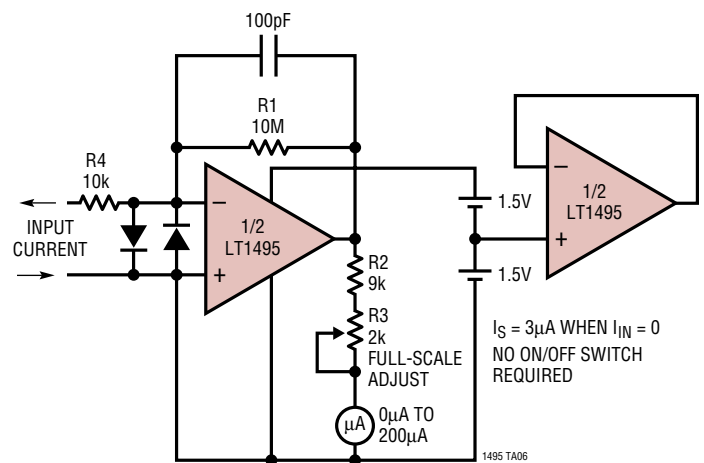
The LT6100 has pin strap connections to establish a variety of accurate gain settings without using external components. For this circuit grounding A2 and leaving A4 open set a gain of 20. Adding one external capacitor to the FIL pin creates a low-pass filter in the signal path. A capacitor of 1000pF as shown sets a filter corner frequency of 2.6KHz.

Gain of 50 Current Sense



The LT6100 is configured for a gain of 50 by grounding both A2 and A4. This is one of the simplest current sensing amplifier circuits where only a sense resistor is required.

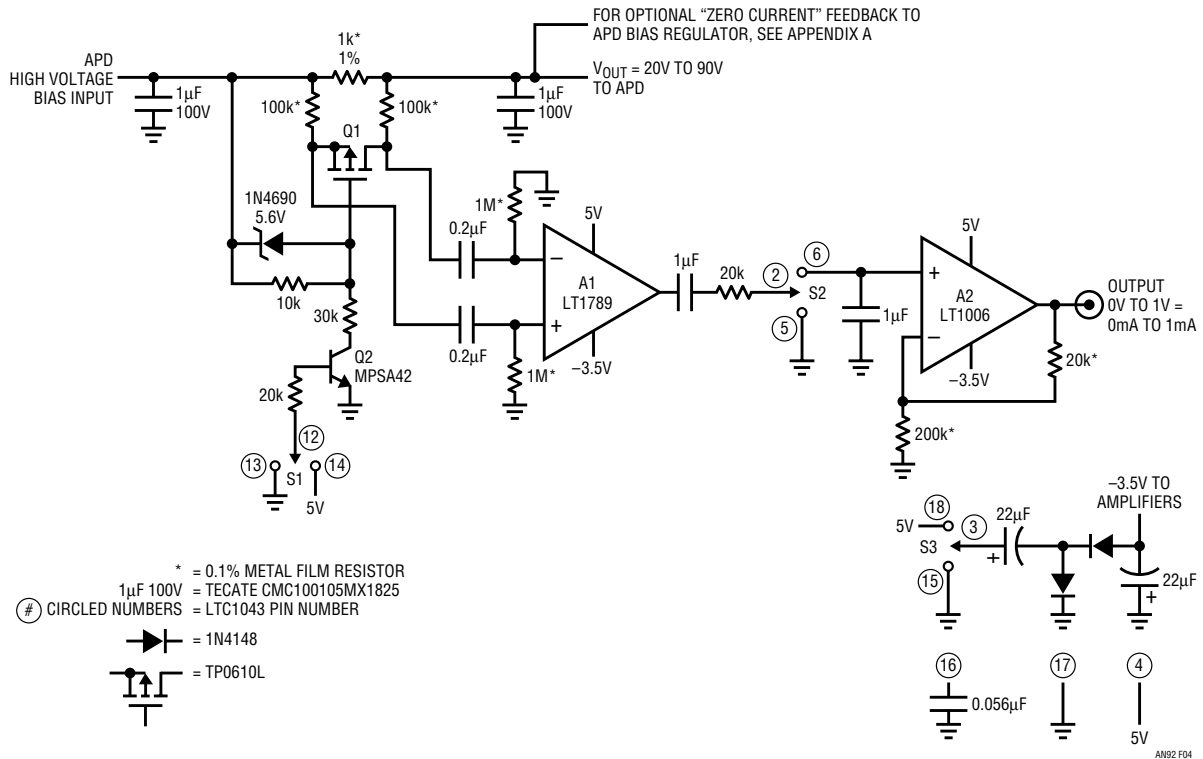
0nA to 200nA Current Meter



A floating amplifier circuit converts a full-scale 200nA flowing in the direction indicated at the inputs to 2V at the output of the LT1495. This voltage is converted to a current to drive a 200uA meter movement. By floating the power to the circuit with batteries, any voltage potential at the inputs are handled. The LT1495 is a micro-power op amp so the quiescent current drain from the batteries is very low and thus no on/off switch is required.

APPLICATION NOTE 105: Current Sense Circuit Collection

Lock-In Amplifier Technique Permits 1% Accurate APD Current Measurement Over 100nA to 1mA Range.



Avalanche Photodiodes, APDs, require a small amount of current from a high voltage supply. The current into the diode is an indication of optical signal strength and must be monitored very accurately. It is desirable to power all of the support circuitry from a single 5V supply.

This circuit utilizes AC carrier modulation techniques to meet APD current monitor requirements. It features 0.4% accuracy over the sensed current range, runs from a 5V supply and has the high noise rejection characteristics of carrier based "lock in" measurements.

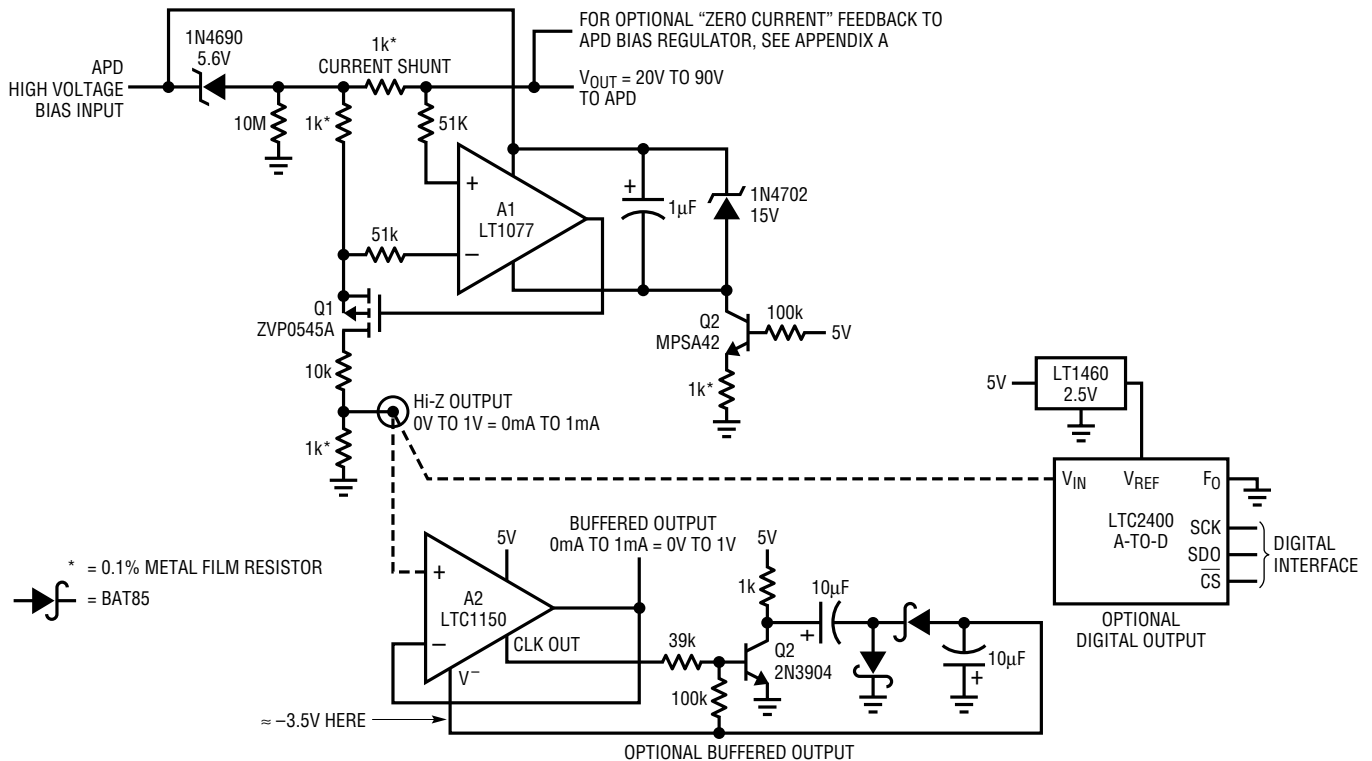
The LTC1043 switch array is clocked by its internal oscillator. Oscillator frequency, set by the capacitor at Pin 16, is about 150Hz. S1 clocking biases Q1 via level shifter Q2. Q1 chops the DC voltage across the 1k current shunt, modulating it into a differential square wave signal

which feeds A1 through 0.2 μ F AC coupling capacitors. A1's single-ended output biases demodulator S2, which presents a DC output to buffer amplifier A2. A2's output is the circuit output.

Switch S3 clocks a negative output charge pump which supplies the amplifier's $V-$ pins, permitting output swing to (and below) zero volts. The 100k resistors at Q1 minimize its on-resistance error contribution and prevent destructive potentials from reaching A1 (and the 5V rail) if either 0.2 μ F capacitor fails. A2's gain of 1.1 corrects for the slight attenuation introduced by A1's input resistors. In practice, it may be desirable to derive the APD bias voltage regulator's feedback signal from the indicated point, eliminating the 1k Ω shunt resistor's voltage drop. Verifying accuracy involves loading the APD bias line with 100nA to 1mA and noting output agreement.

APPLICATION NOTE 105: Current Sense Circuit Collection

DC Coupled APD Current Monitor



AN92 F05

Avalanche Photodiodes, APDs, require a small amount of current from a high voltage supply. The current into the diode is an indication of optical signal strength and must be monitored very accurately. It is desirable to power all of the support circuitry from a single 5V supply.

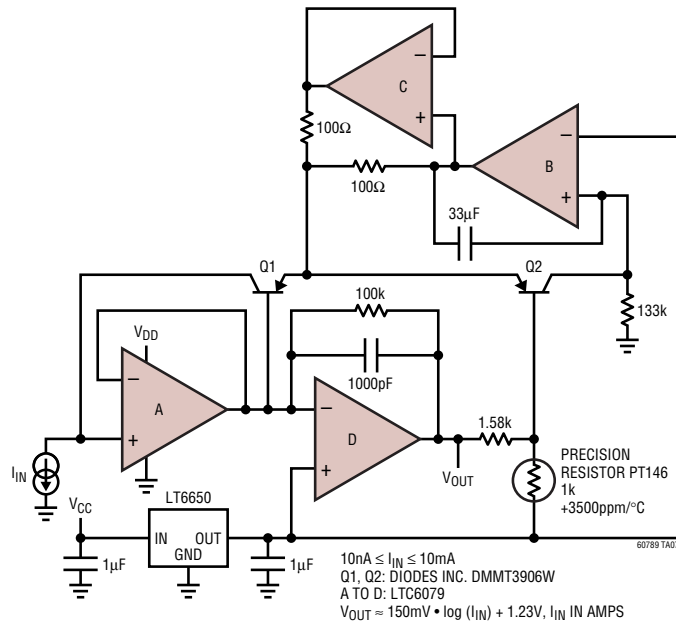
This circuit's DC coupled current monitor eliminates the previous circuit's trim but pulls more current from the APD bias supply. A1 floats, powered by the APD bias rail. The 15V zener diode and current source Q2 ensure A1 never is exposed to destructive voltages. The 1kΩ current shunt's voltage drop sets A1's positive input potential. A1 balances its inputs by feedback controlling its negative input via Q1. As such, Q1's source voltage equals A1's positive input voltage and its drain current sets the voltage across its source resistor. Q1's drain current produces a voltage drop across the ground referred 1kΩ resistor identical to the drop across the 1kΩ current shunt and, hence, APD current. This relationship holds

across the 20V to 90V APD bias voltage range. The 5.6V zener assures A1's inputs are always within their common mode operating range and the 10MΩ resistor maintains adequate zener current when APD current is at very low levels.

Two output options are shown. A2, a chopper stabilized amplifier, provides an analog output. Its output is able to swing to (and below) zero because its V₋ pin is supplied with a negative voltage. This potential is generated by using A2's internal clock to activate a charge pump which, in turn, biases A2's V₋ pin.³ A second output option substitutes an A-to-D converter, providing a serial format digital output. No V₋ supply is required, as the LTC2400 A-to-D will convert inputs to (and slightly below) zero volts.

APPLICATION NOTE 105: Current Sense Circuit Collection

Six Decade (10nA to 10mA) Current Log Amplifier



Using precision quad amplifiers like the LTC6079, ($10\mu\text{V}$ offset and $<1\text{pA}$ bias current) allow for very wide range current sensing. In this circuit a six decade range of current pulled from the circuit input terminal is converted to an output voltage in logarithmic fashion increasing 150mV for every decade of current change.

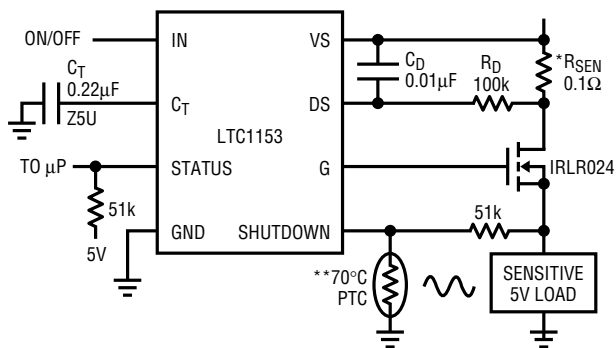
APPLICATION NOTE 105: Current Sense Circuit Collection

Motors and Inductive Loads

The largest challenge in measuring current through inductive circuits is the transients of voltage that often occur. Current flow can remain continuous in one direction while the voltage across the sense terminals reverses in polarity.

To see other chapters in this Application Note, return to the [Introduction](#).

Electronic Circuit Breaker

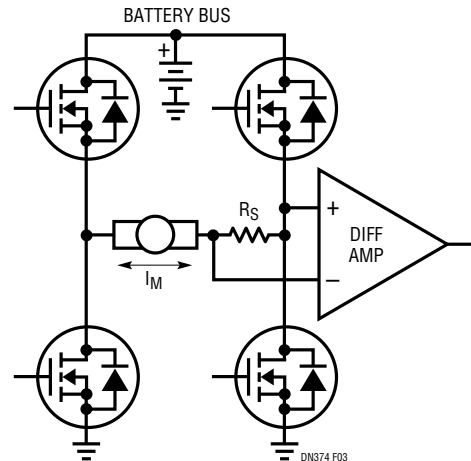


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** RL2006-100-70-30-PT1 KEystone CARBON COMPANY (814) 781-1591

LTC1153 • TA01

The LTC1153 is an Electronic Circuit Breaker. Sensed current to a load opens the breaker when 100mV is developed between the supply input, VS, and the Drain Sense pin, DS. To avoid transient, or nuisance trips of the break components RD and CD delay the action for 1msec. A thermistor can also be used to bias the Shutdown input to monitor heat generated in the load and remove power should the temperature exceed 70°C in this example. A feature of the LTC1153 is timed Automatic Reset which will try to re-connect the load after 200msec using the 0.22µF timer capacitor shown.

Conventional H-Bridge Current Monitor

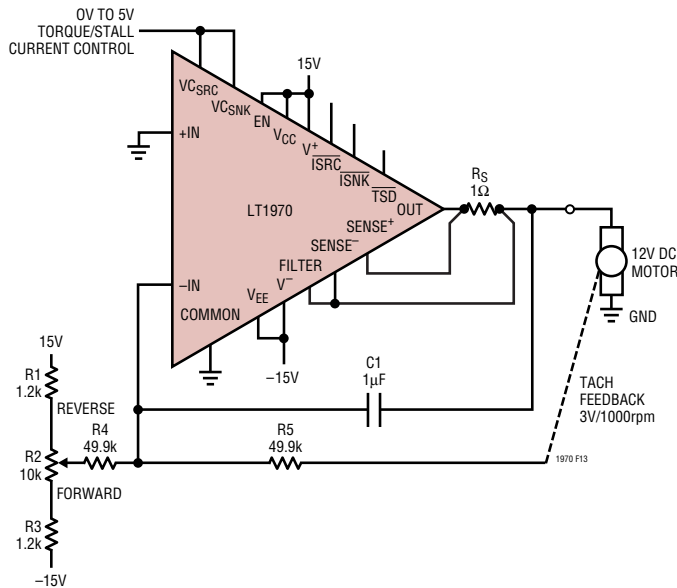


Many of the newer electric drive functions, such as steering assist, are bidirectional in nature. These functions are generally driven by H-bridge MOSFET arrays using pulse-width-modulation (PWM) methods to vary the commanded torque. In these systems, there are two main purposes for current monitoring. One is to monitor the current in the load, to track its performance against the desired command (i.e., closed-loop servo law), and another is for fault detection and protection features.

A common monitoring approach in these systems is to amplify the voltage on a “flying” sense resistor, as shown. Unfortunately, several potentially hazardous fault scenarios go undetected, such as a simple short to ground at a motor terminal. Another complication is the noise introduced by the PWM activity. While the PWM noise may be filtered for purposes of the servo law, information useful for protection becomes obscured. The best solution is to simply provide two circuits that individually protect each half-bridge and report the bidirectional load current. In some cases, a smart MOSFET bridge driver may already include sense resistors and offer the protection features needed. In these situations, the best solution is the one that derives the load information with the least additional circuitry.

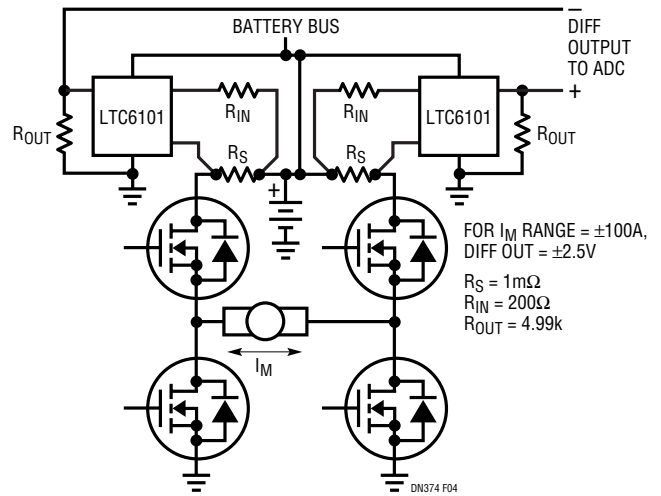
APPLICATION NOTE 105: Current Sense Circuit Collection

Motor Speed Control



This uses an LT1970 power amplifier as a linear driver of a DC motor with speed control. The ability to source and sink the same amount of output current provides for bidirectional rotation of the motor. Speed control is managed by sensing the output of a tachometer built on to the motor. A typical feedback signal of 3V/1000rpm is compared with the desired speed-set input voltage. Because the LT1970 is unity-gain stable, it can be configured as an integrator to force whatever voltage across the motor as necessary to match the feedback speed signal with the set input signal. Additionally, the current limit of the amplifier can be adjusted to control the torque and stall current of the motor.

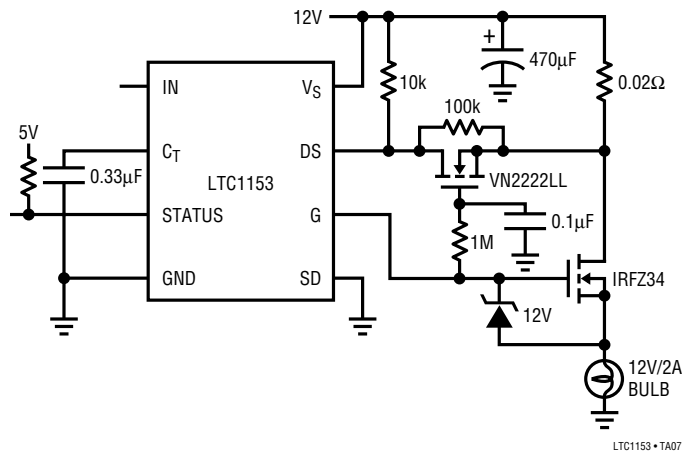
Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information



This circuit implements a differential load measurement for an ADC using twin unidirectional sense measurements. Each LTC6101 performs high side sensing that rapidly responds to fault conditions, including load shorts and MOSFET failures. Hardware local to the switch module (not shown in the diagram) can provide the protection logic and furnish a status flag to the control system. The two LTC6101 outputs taken differentially produce a bidirectional load measurement for the control servo. The ground-referenced signals are compatible with most $\Delta\Sigma$ ADCs. The $\Delta\Sigma$ ADC circuit also provides a "free" integration function that removes PWM content from the measurement. This scheme also eliminates the need for analog-to-digital conversions at the rate needed to support switch protection, thus reducing cost and complexity.

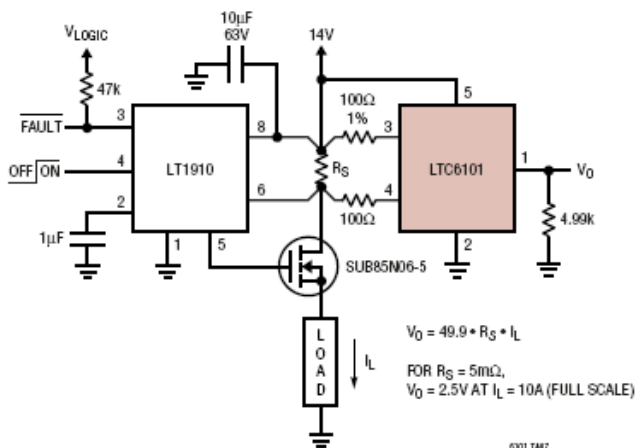
APPLICATION NOTE 105: Current Sense Circuit Collection

Lamp Driver



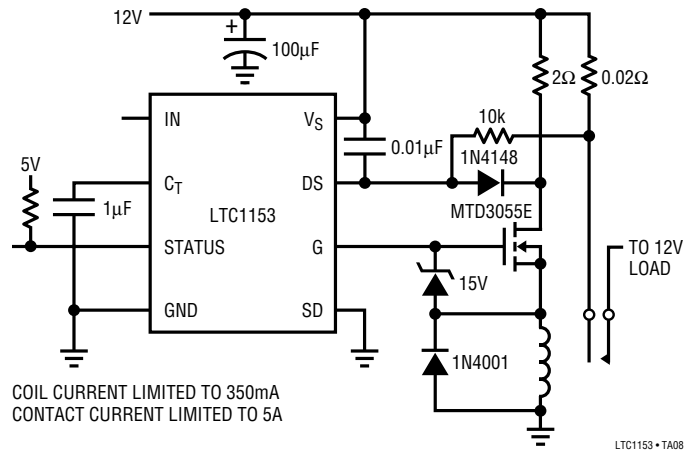
The inrush current created by a lamp during turn-on can be 10 to 20 times greater than the rated operating current. This circuit shifts the trip threshold of an LTC1153 Electronic Circuit Breaker up by a factor of 11:1 (to 30A) for 100ms while the bulb is turned on. The trip threshold then drops down to 2.7A after the inrush current has subsided.

Intelligent High Side Switch



The LT1910 is a dedicated high side MOSFET driver with built in protection features. It provides the gate drive for a power switch from standard logic voltage levels. It provides shorted load protection by monitoring the current flow to through the switch. Adding an LTC6101 to the same circuit, sharing the same current sense resistor, provides a linear voltage signal proportional to the load current for additional intelligent control.

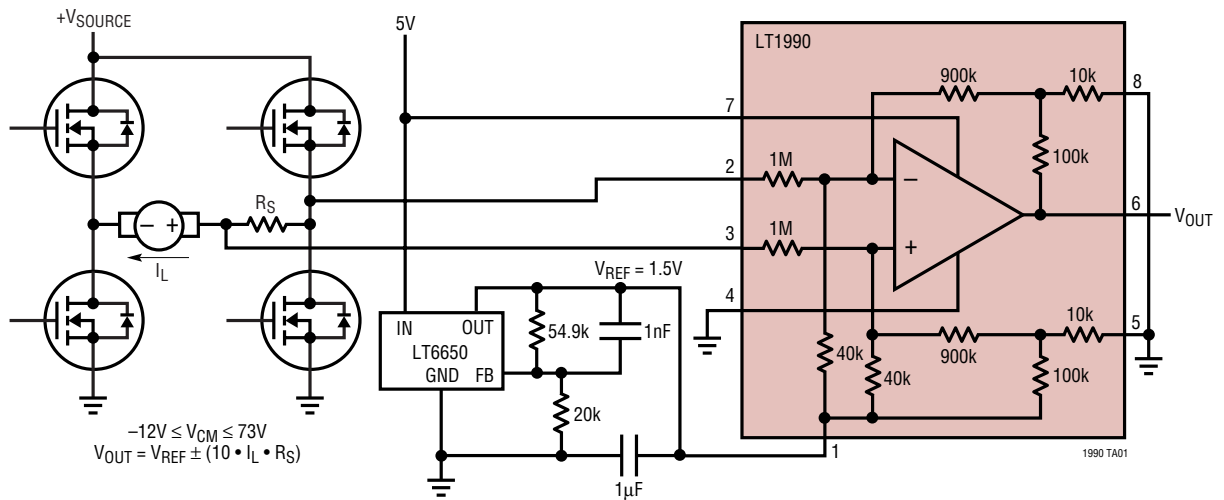
Relay Driver



This circuit provides reliable control of a relay by using an Electronic Circuit Breaker circuit with two-level over-current protection. Current flow is sensed through two separate resistors, one for the current into the relay coil and the other for the current through the relay contacts. When 100mV is developed between the Vs supply pin and the Drain Sense pin, DS, the N-channel MOSFET is turned off opening the contacts. As shown, the relay coil current is limited to 350mA and the contact current to 5 Amps.

APPLICATION NOTE 105: Current Sense Circuit Collection

Full-Bridge Load Current Monitor



The LT1990 is a difference amplifier that features a very wide common mode input voltage range that can far exceed its own supply voltage. This is an advantage to reject transient voltages when used to monitor the current in a full bridge driven inductive load such as a motor. The LT6650 provides a voltage reference of 1.5V to bias up

the output away from ground. The output will move above or below 1.5V as a function of which direction the current in the load is flowing. As shown, the amplifier provides a gain of 10 to the voltage developed across resistor R_S .

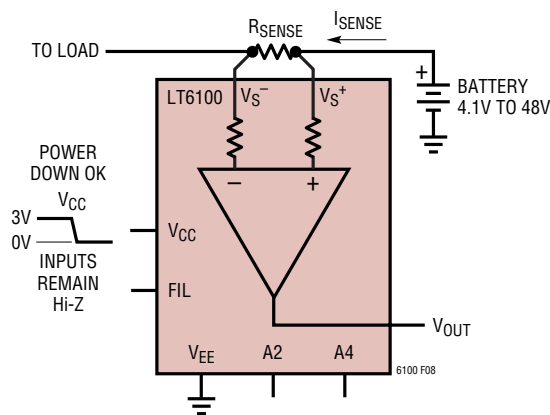
APPLICATION NOTE 105: Current Sense Circuit Collection

Batteries

The science of battery chemistries and the charging and discharging characteristics is a book of its own. This chapter is intended to provide a few examples of monitoring current flow into and out of batteries of any chemistry.

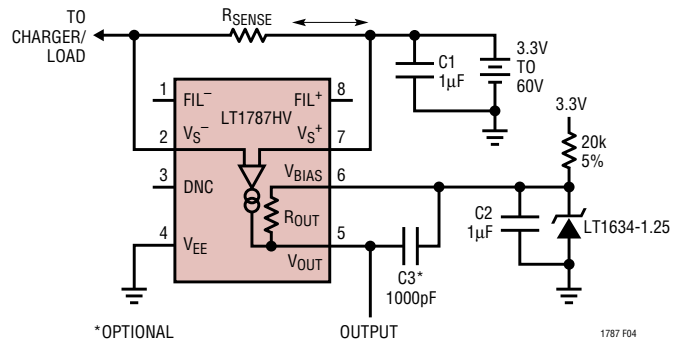
To see other chapters in this Application Note, return to the [Introduction](#).

Input Remains Hi-Z when LT6100 is Powered Down



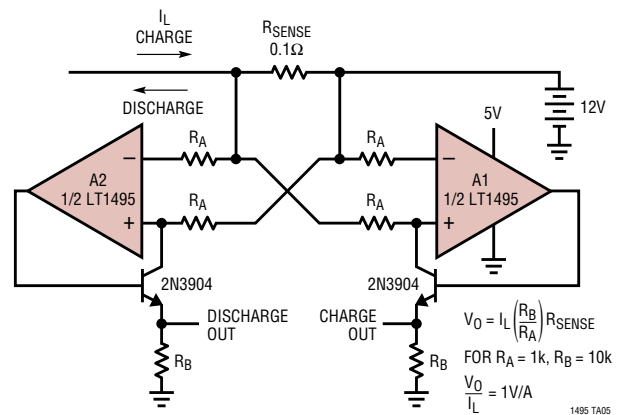
This is the typical configuration for an LT6100, monitoring the load current of a battery. The circuit is powered from a low-voltage supply rail rather than the battery being monitored. A unique benefit of this configuration is that when the LT6100 is powered down, its battery sense inputs remain high impedance, drawing less than 1 μ A of current. This is due to an implementation of Linear Technology's Over-The-Top[®] input technique at its front end.

Charge/Discharge Current Monitor on Single Supply with Shifted V_{BIAS}



Here the LT1787 is used in a single supply mode with the V_{BIAS} pin shifted positive using an external LT1634 voltage reference. The V_{OUT} output signal can swing above and below V_{BIAS} to allow monitoring of positive or negative currents through the sense resistor. The choice of reference voltage is not critical except for the precaution that adequate headroom must be provided for V_{OUT} to swing without saturating the internal circuitry. The component values shown allow operation with V_S supplies as low as 3.1V.

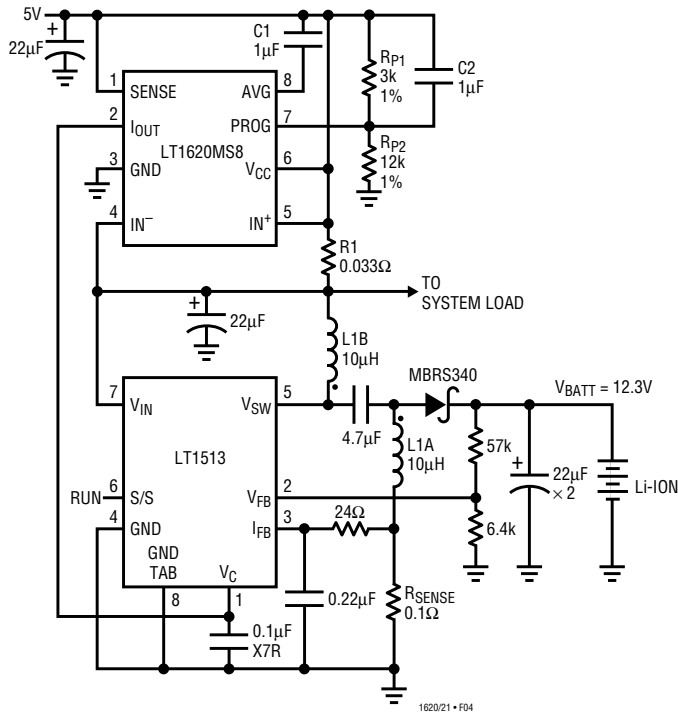
Battery Current Monitor



One LT1495 dual op-amp package can be used to establish separate charge and discharge current monitoring outputs. The LT1495 features Over-the-Top operation allowing the battery potential to be as high as 36V with only a 5V amplifier supply voltage.

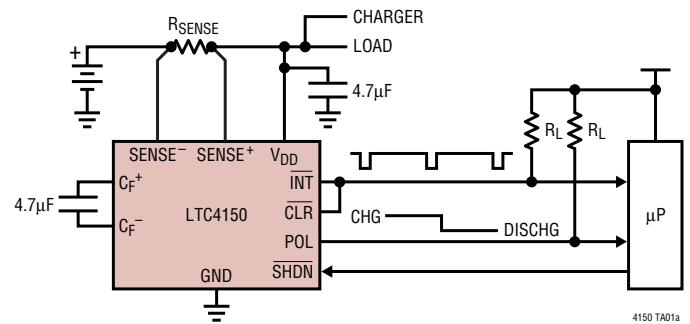
APPLICATION NOTE 105: Current Sense Circuit Collection

Input Current Sensing Application



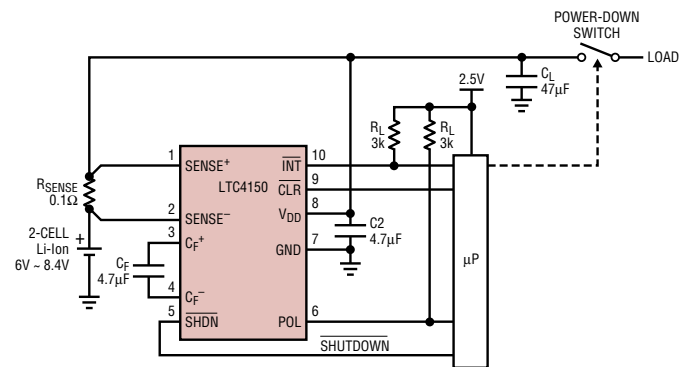
The LT1620 is coupled with an LT1513 SEPIC battery charger IC to create an input over current protected charger circuit. The programming voltage ($V_{CC} - V_{PROG}$) is set to 1.0V through a resistor divider (R_{P1} and R_{P2}) from the 5V input supply to ground. In this configuration, if the input current drawn by the battery charger combined with the system load requirements exceeds a current limit threshold of 3A, the battery charger current will be reduced by the LT1620 such that the total input supply current is limited to 3A.

Coulomb Counter



The LTC4150 is a micropower high-side sense circuit that includes a V/F function. Voltage across the sense resistor is cyclically integrated and reset to provide digital transitions that represent charge flow to or from the battery. A polarity bit indicates the direction of the current. Supply potential for the LTC4150 is 2.7V to 8.5V. In the free-running mode (as shown, with CLR & INT connected together) the pulses are approximately 1μs wide and around 1Hz full-scale.

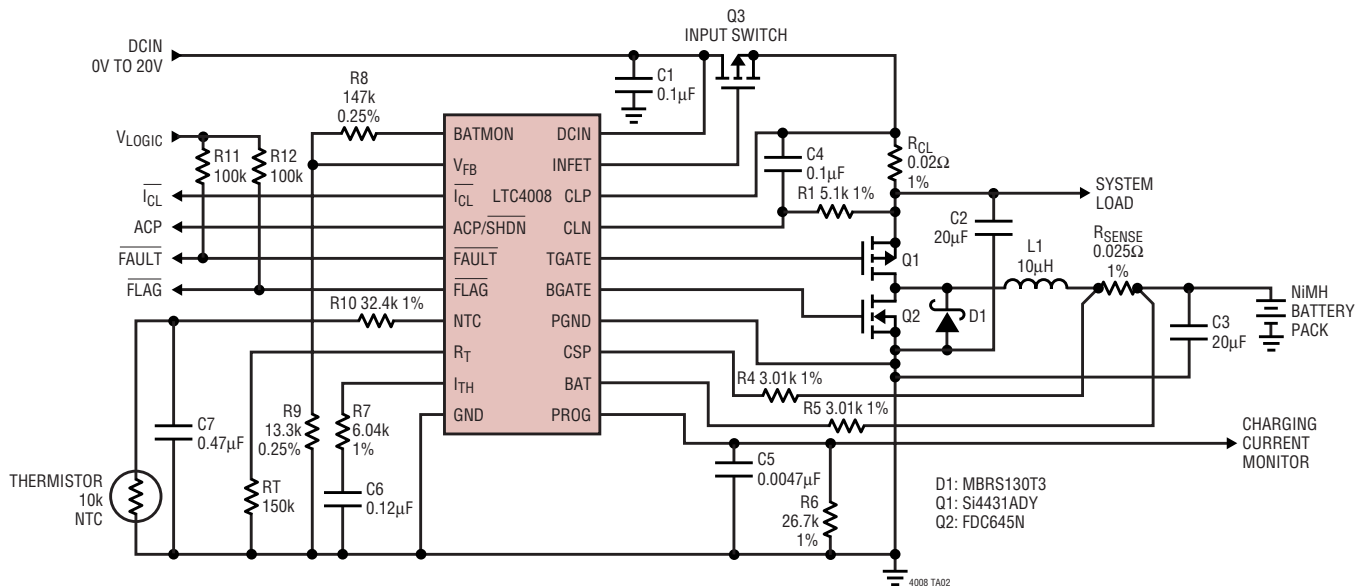
Li-Ion Gas Gauge



This is the same as the Coulomb Counter circuit, except that the microprocessor clears the integration cycle complete condition with software, so that a relatively slow polling routine may be used.

APPLICATION NOTE 105: Current Sense Circuit Collection

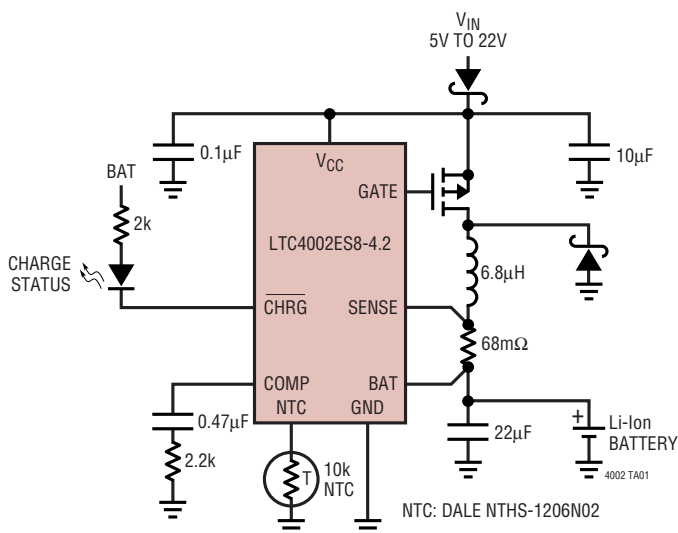
NiMH Charger



The LTC4008 is a complete NiMH battery pack controller. It provides automatic switchover to battery power when the external DC power source is removed. When power is

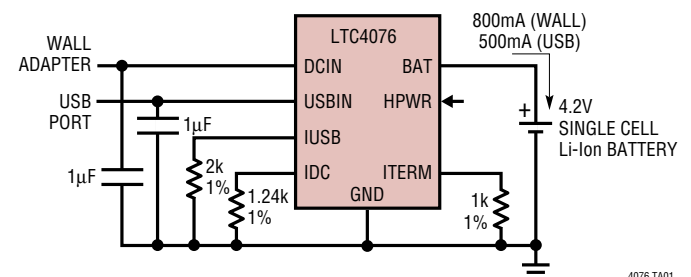
connected the battery pack is always kept charged and ready for duty.

Single Cell Li-Ion Charger



Controlling the current flow in Lithium-Ion battery chargers is essential for safety and extending useful battery life. Intelligent battery charger ICs can be used in fairly simple circuits to monitor and control current, voltage and even battery pack temperature for fast and safe charging.

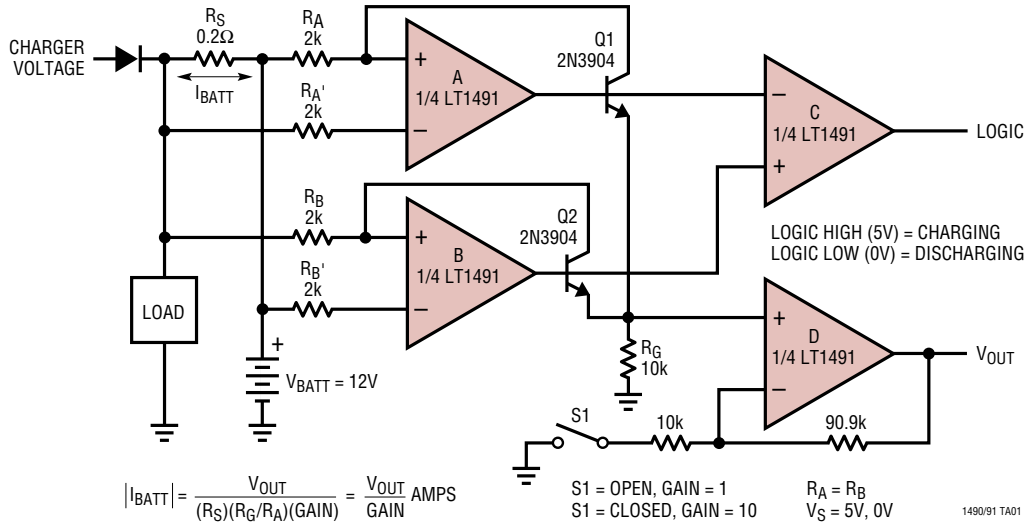
Li-Ion Charger



Just a few external components are required for this single Li-Ion cell charger. Power for the charger can come from a wall adapter or a computer's USB port.

APPLICATION NOTE 105: Current Sense Circuit Collection

Battery Monitor



Op-amp sections A & B form classical high-side sense circuits in conjunction with Q1 & Q2 respectively. Each section handles a different polarity of battery current flow and delivers metered current to load resistor R_G. Section C operates as a comparator to provide a logic signal indi-

cating whether the current is a charge or discharge flow. S1 sets the section D buffer op-amp gain to +1 or +10. Rail-to-Rail op-amps are required in this circuit, such as the LT1491 quad in the example.

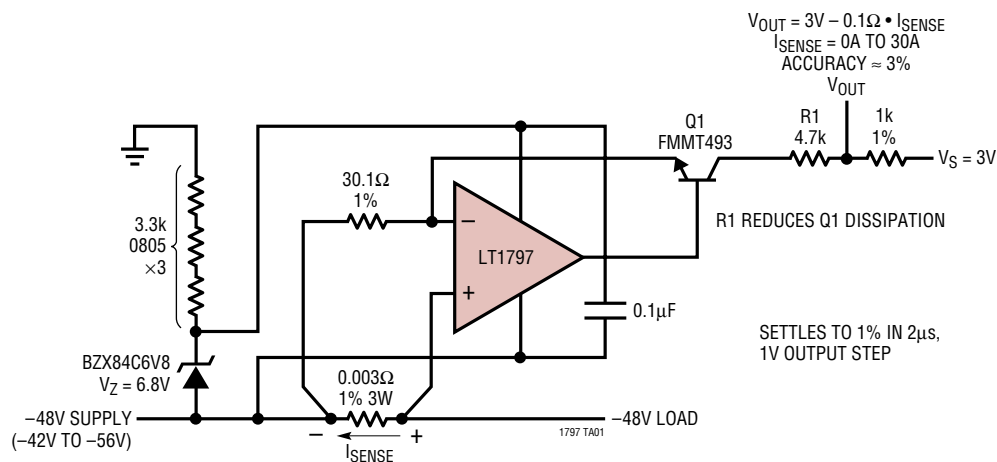
APPLICATION NOTE 105: Current Sense Circuit Collection

High Speed

Current monitoring is not normally a particularly high speed requirement unless excessive current flow is caused by a fault of some sort. The use of fast amplifiers in conventional current sense circuits is usually sufficient to obtain the response time desired.

To see other chapters in this Application Note, return to the [Introduction](#).

Fast Compact -48V Current Sense

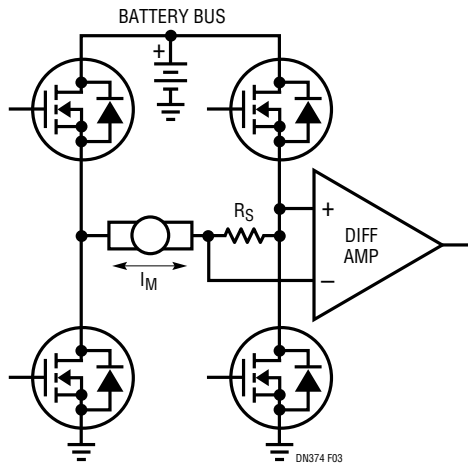


This amplifier configuration is essentially the complementary implementation to the classic high-side configuration. The op amp used must support common-mode operation at its lower rail. A “floating” shunt-regulated local supply is provided by the Zener diode, and the transistor provides metered current to an output load

resistance ($1k\Omega$ in this circuit). In this circuit, the output voltage is referenced to a positive potential and moves downward when representing increasing -48V loading. Scaling accuracy is set by the quality of resistors used and the performance of the NPN transistor.

APPLICATION NOTE 105: Current Sense Circuit Collection

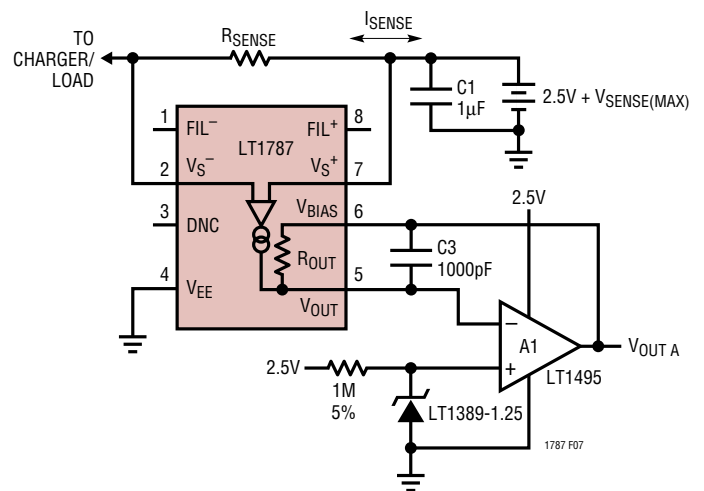
Conventional H-Bridge Current Monitor



Many of the newer electric drive functions, such as steering assist, are bidirectional in nature. These functions are generally driven by H-bridge MOSFET arrays using pulse-width-modulation (PWM) methods to vary the commanded torque. In these systems, there are two main purposes for current monitoring. One is to monitor the current in the load, to track its performance against the desired command (i.e., closed-loop servo law), and another is for fault detection and protection features.

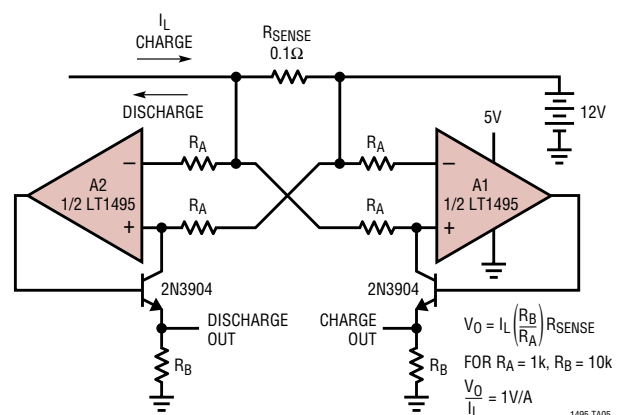
A common monitoring approach in these systems is to amplify the voltage on a “flying” sense resistor, as shown. Unfortunately, several potentially hazardous fault scenarios go undetected, such as a simple short to ground at a motor terminal. Another complication is the noise introduced by the PWM activity. While the PWM noise may be filtered for purposes of the servo law, information useful for protection becomes obscured. The best solution is to simply provide two circuits that individually protect each half-bridge and report the bidirectional load current. In some cases, a smart MOSFET bridge driver may already include sense resistors and offer the protection features needed. In these situations, the best solution is the one that derives the load information with the least additional circuitry.

Single Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter



The LT1787’s output is buffered by an LT1495 rail-to-rail op-amp configured as an I/V converter. This configuration is ideal for monitoring very low voltage supplies. The LT1787’s V_{OUT} pin is held equal to the reference voltage appearing at the op amp’s non-inverting input. This allows one to monitor supply voltages as low as 2.5V. The op-amp’s output may swing from ground to its positive supply voltage. The low impedance output of the op amp may drive following circuitry more effectively than the high output impedance of the LT1787. The I/V converter configuration also works well with split supply voltages.

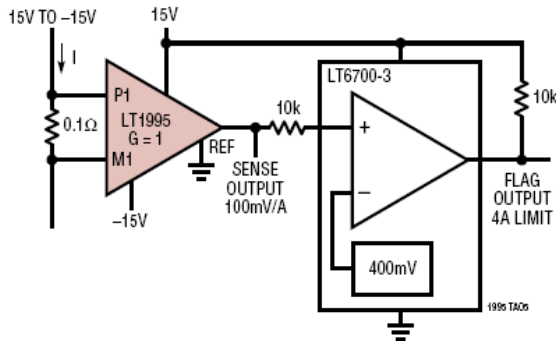
Battery Current Monitor



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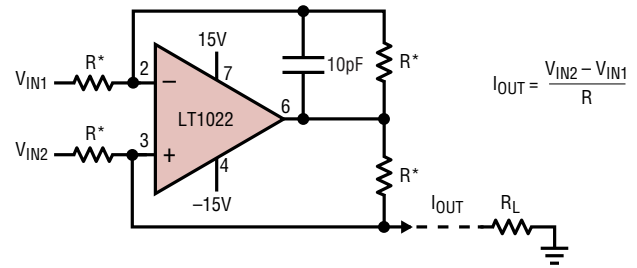
APPLICATION NOTE 105: Current Sense Circuit Collection

Fast Current Sense with Alarm



The LT1995 is shown as a simple unity gain difference amplifier. When biased with split supplies the input current can flow in either direction providing an output voltage of 100mV per Amp from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/usec slew rate the response of this sense amplifier is fast. Adding a simple comparator with a built in reference voltage circuit such as the LT6700-3 can be used to generate an over-current flag. With the 400mV reference the flag occurs at 4A.

Fast Differential Current Source



*MATCH TO 0.01%
 FULL-SCALE POWER BANDWIDTH
 = 1MHz FOR $I_{OUT}R = 8V_{P-P}$
 = 400kHz FOR $I_{OUT}R = 20V_{P-P}$
 MAXIMUM $I_{OUT} = 10mA_{P-P}$
 COMMON-MODE VOLTAGE AT LT1022 INPUT = $\frac{I_{OUTP-P} \cdot R_L}{2}$

LT1022 • TA07

This is a variation on the Howland configuration, where load current actually passes through a feedback resistor as an implicit sense resistance. Since the effective sense resistance is relatively large, this topology is appropriate for producing small controlled currents.

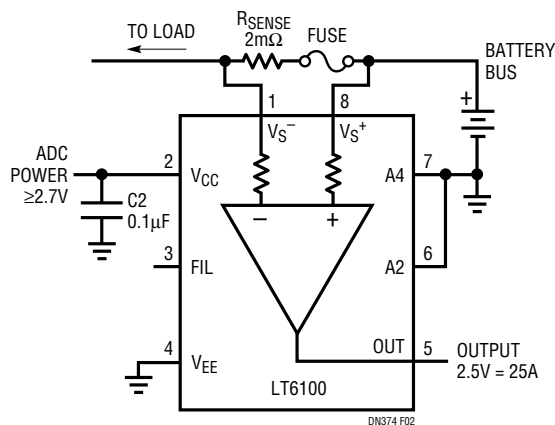
APPLICATION NOTE 105: Current Sense Circuit Collection

Fault Sensing

The lack of current flow or the dramatic increase of current flow very often indicates a system fault. In these circuits it is important to not only detect the condition, but also ensure the safe operation of the detection circuitry itself. System faults can be destructive in many unpredictable ways.

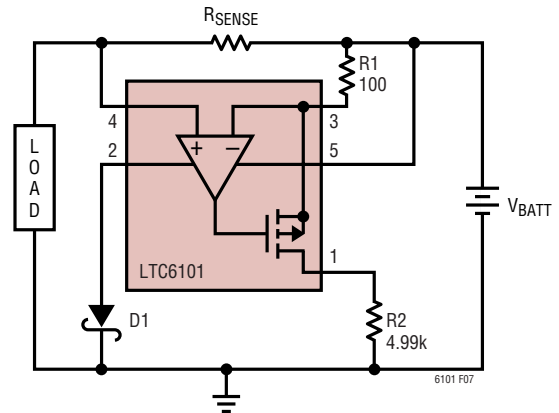
To see other chapters in this Application Note, return to the [Introduction](#).

High Side Current Sense and Fuse Monitor



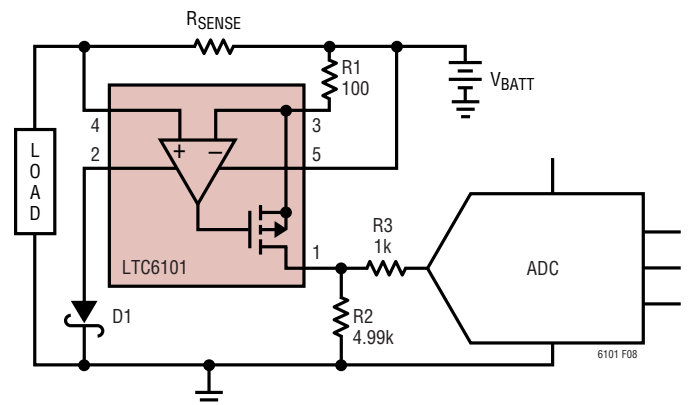
The LT6100 can be used as a combination current sensor and fuse monitor. This part includes on-chip output buffering and was designed to operate with the low supply voltage ($\geq 2.7V$), typical of vehicle data acquisition systems, while the sense inputs monitor signals at the higher battery bus potential. The LT6100 inputs are tolerant of large input differentials, thus allowing the blown-fuse operating condition (this would be detected by an output full-scale indication). The LT6100 can also be powered down while maintaining high impedance sense inputs, drawing less than $1\mu A$ max from the battery bus.

Schottky Prevents Damage During Supply Reversal



The LTC6101 is not protected internally from external reversal of supply polarity. To prevent damage that may occur during this condition, a Schottky diode should be added in series with V^- . This will limit the reverse current through the LTC6101. Note that this diode will limit the low voltage performance of the LTC6101 by effectively reducing the supply voltage to the part by V_D .

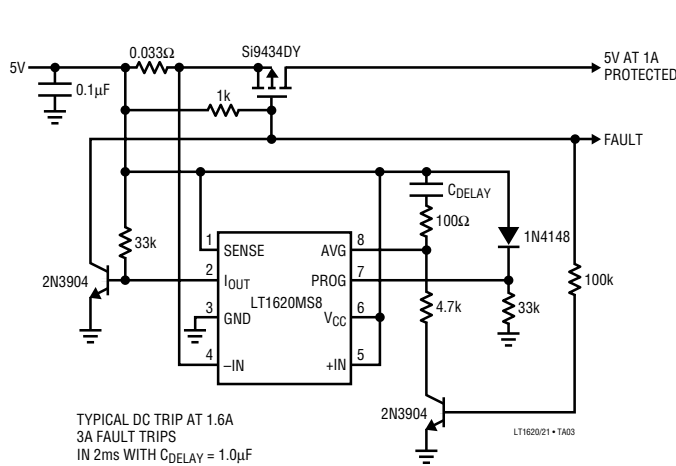
Additional Resistor R3 Protects Output During Supply Reversal



If the output of the LTC6101 is wired to an independently powered device that will effectively short the output to another rail or ground (such as through an ESD protection clamp) during a reverse supply condition, the LTC6101's output should be connected through a resistor or Schottky diode to prevent excessive fault current.

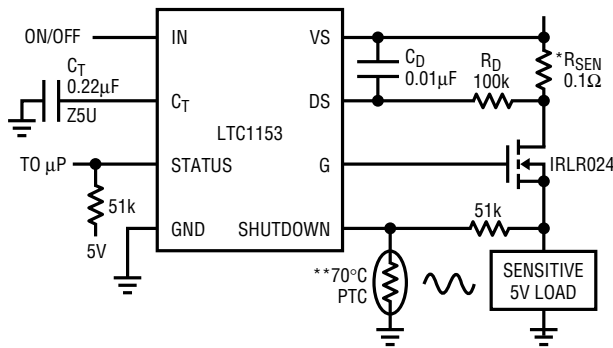
APPLICATION NOTE 105: Current Sense Circuit Collection

Electronic Circuit Breaker



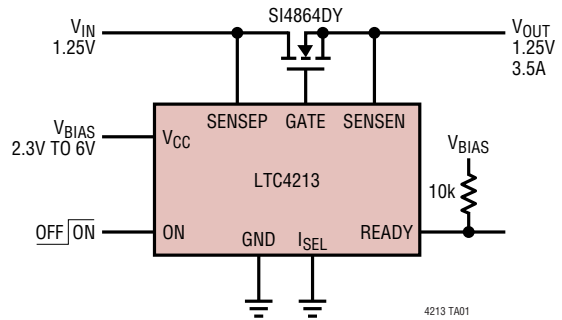
The LT1620I current sense amplifier is used to detect an over-current condition and shut off a P-MOSFET load switch. A fault flag is produced in the over-current condition and a self-reset sequence is initiated.

Electronic Circuit Breaker



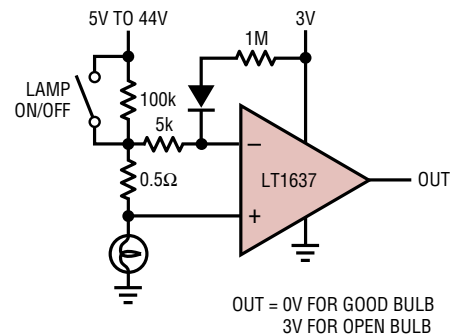
The LTC1153 is an Electronic Circuit Breaker. Sensed current to a load opens the breaker when 100mV is developed between the supply input, V_S , and the Drain Sense pin, DS. To avoid transient, or nuisance trips of the break components R_D and C_D delay the action for 1msec. A thermistor can also be used to bias the Shutdown input to monitor heat generated in the load and remove power should the temperature exceed 70°C in this example. A feature of the LTC1153 is timed Automatic Reset which will try to re-connect the load after 200msec using the 0.22μF timer capacitor shown.

1.25V Electronic Circuit Breaker



The LTC4213 provides protection and automatic circuit breaker action by sensing Drain-to-Source voltage-drop across the NMOSFET. The sense inputs have a Rail-to-Rail common mode range, so the circuit breaker can protect bus voltages from 0V up to 6V. Logic signals flag a trip condition (with the READY output signal) and reinitialize the breaker (using the ON input). The ON input may also be used as a command in a “smart switch” application.

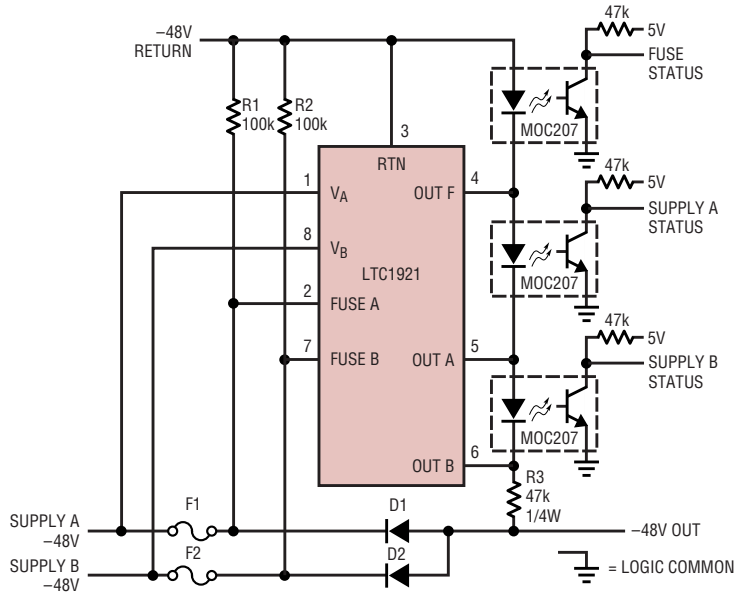
Lamp Outage Detector



In this circuit, the lamp is monitored in both the on and off condition for continuity. In the off condition, the filament pull-down action creates a small test current in the 5kΩ that is detected to indicate a good lamp. If the lamp is open, the 100kΩ pull-up, or the relay contact, provides the op-amp bias current through the 5kΩ, that is opposite in polarity. When the lamp is powered and filament current is flowing, the drop in the 0.05Ω sense resistor will exceed that of the 5kΩ and a lamp-good detection will still occur. This circuit requires particular Over-the-Top input characteristics for the op-amp, so part substitutions are discouraged (however, this same circuit also works properly with an LT1716 comparator, also an Over-the-Top part).

APPLICATION NOTE 105: Current Sense Circuit Collection

Simple Telecom Power Supply Fuse Monitor



V _A	V _B	SUPPLY A STATUS	SUPPLY B STATUS
OK	OK	0	0
OK	UV OR OV	0	1
UV OR OV	OK	1	0
UV OR OV	UV OR OV	1	1

OK: WITHIN SPECIFICATION
 OV: OVERVOLTAGE
 UV: UNDERVOLTAGE

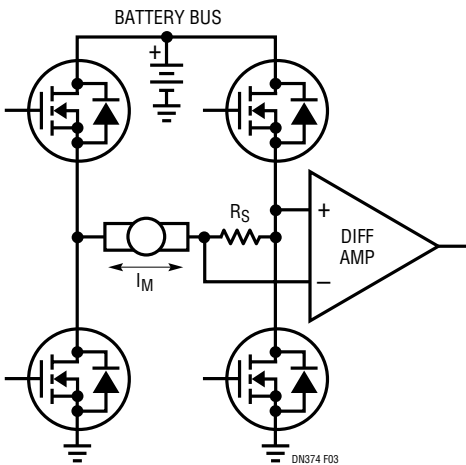
V _{FUSE A}	V _{FUSE B}	FUSE STATUS
= V _A	= V _B	0
= V _A	≠ V _B	1
≠ V _A	= V _B	1
≠ V _A	≠ V _B	1*

0: LED/PHOTODIODE ON
 1: LED/PHOTODIODE OFF
 *IF BOTH FUSES (F1 AND F2) ARE OPEN,
 ALL STATUS OUTPUTS WILL BE HIGH
 SINCE R3 WILL NOT BE POWERED

The LTC1921 provides an all-in-one telecom fuse and supply-voltage monitoring function. Three opto-isolated

status flags are generated that indicate the condition of the supplies and the fuses.

Conventional H-Bridge Current Monitor

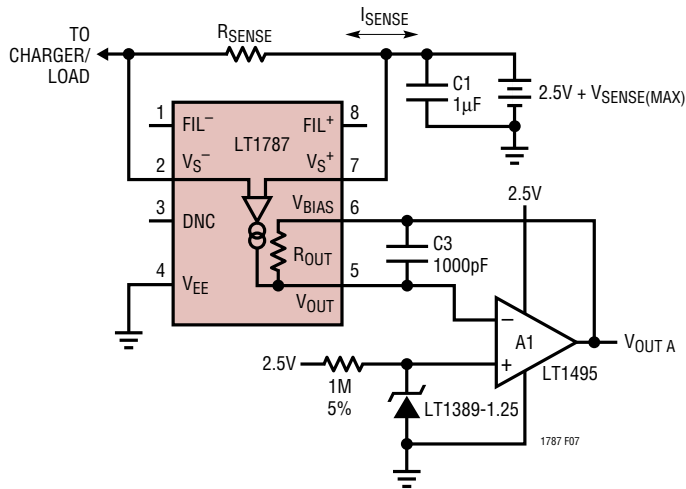


Many of the newer electric drive functions, such as steering assist, are bidirectional in nature. These functions are generally driven by H-bridge MOSFET arrays using pulse-width-modulation (PWM) methods to vary the commanded torque. In these systems, there are two main purposes for current monitoring. One is to monitor the current in the load, to track its performance against the desired command (i.e., closed-loop servo law), and another is for fault detection and protection features.

A common monitoring approach in these systems is to amplify the voltage on a “flying” sense resistor, as shown. Unfortunately, several potentially hazardous fault scenarios go undetected, such as a simple short to ground at a motor terminal. Another complication is the noise introduced by the PWM activity. While the PWM noise may be filtered for purposes of the servo law, information useful for protection becomes obscured. The best solution is to simply provide two circuits that individually protect each half-bridge and report the bidirectional load current. In some cases, a smart MOSFET bridge driver may already include sense resistors and offer the protection features needed. In these situations, the best solution is the one that derives the load information with the least additional circuitry.

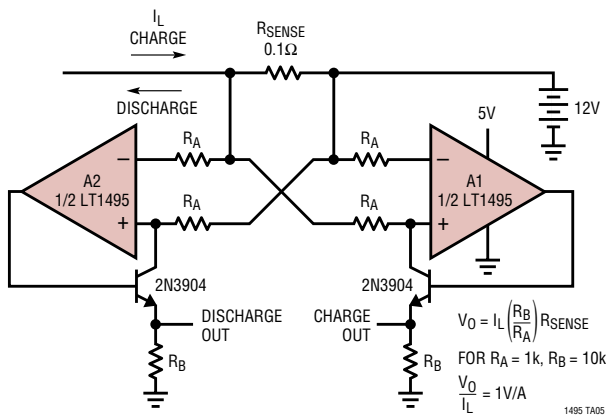
APPLICATION NOTE 105: Current Sense Circuit Collection

Single Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter



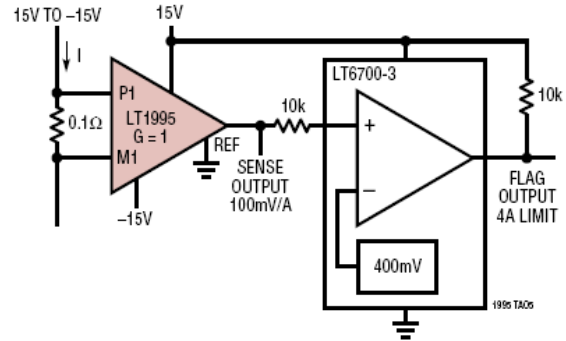
The LT1787's output is buffered by an LT1495 rail-to-rail op-amp configured as an I/V converter. This configuration is ideal for monitoring very low voltage supplies. The LT1787's V_{OUT} pin is held equal to the reference voltage appearing at the op amp's non-inverting input. This allows one to monitor supply voltages as low as 2.5V. The op-amp's output may swing from ground to its positive supply voltage. The low impedance output of the op amp may drive following circuitry more effectively than the high output impedance of the LT1787. The I/V converter configuration also works well with split supply voltages.

Battery Current Monitor



One LT1495 dual op-amp package can be used to establish separate charge and discharge current monitoring outputs. The LT1495 features Over-the-Top operation allowing the battery potential to be as high as 36V with only a 5V amplifier supply voltage.

Fast Current Sense with Alarm



The LT1995 is shown as a simple unity gain difference amplifier. When biased with split supplies the input current can flow in either direction providing an output voltage of 100mV per Amp from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/usec slew rate the response of this sense amplifier is fast. Adding a simple comparator with a built in reference voltage circuit such as the LT6700-3 can be used to generate an over-current flag. With the 400mV reference the flag occurs at 4A.

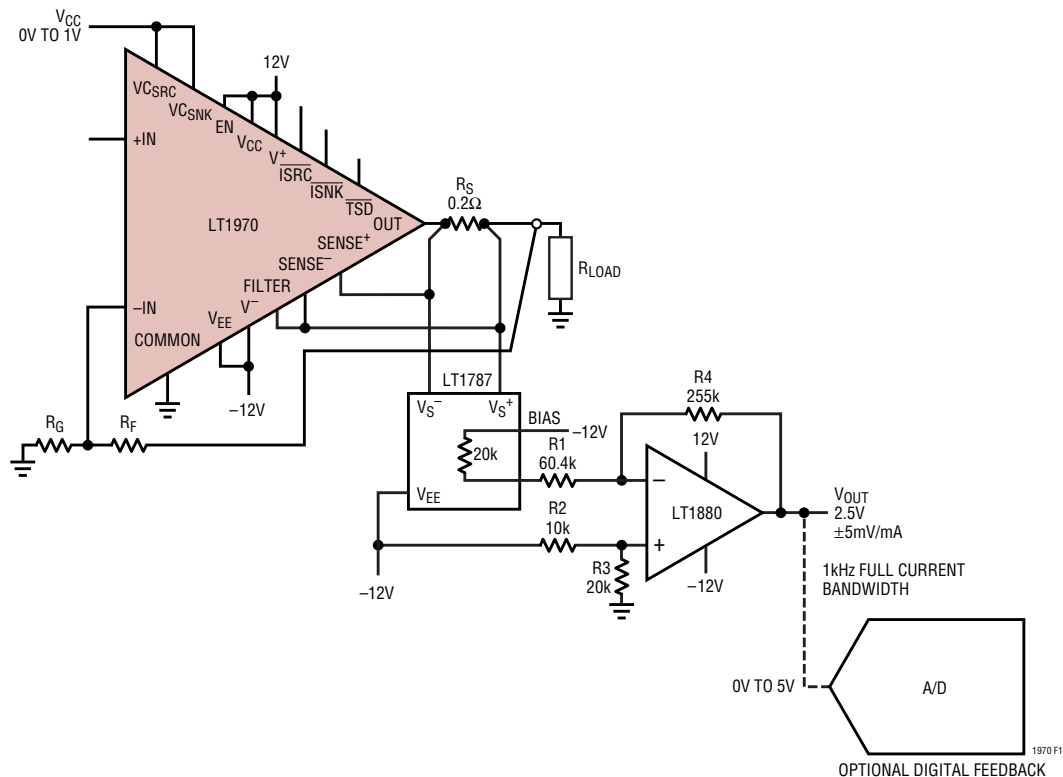
APPLICATION NOTE 105: Current Sense Circuit Collection

Digitizing

In many systems the analog voltage quantity indicating current flow must be input to a system controller. In this chapter several examples of the direct interface of a current sense amplifier to an A to D converter are shown.

To see other chapters in this Application Note, return to the [Introduction](#).

Sensing Output Current

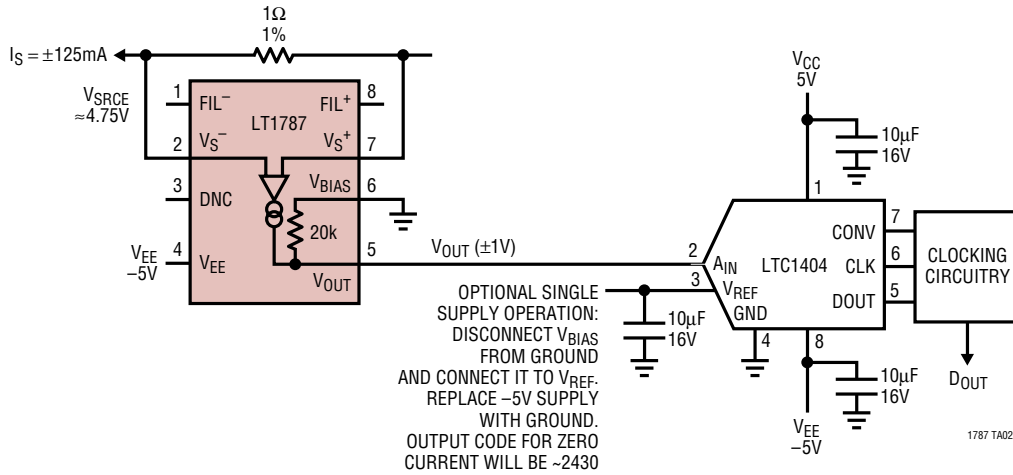


The LT1970 is a 500mA power amplifier with voltage programmable output current limit. Separate DC voltage inputs and an output current sensing resistor control the maximum sourcing and sinking current values. These control voltages could be provided by a D-to-A Converter

in a microprocessor controlled system. For closed loop control of the current to a load an LT1787 can monitor the output current. The LT1880 op amp provides scaling and level shifting of the voltage applied to an A-to-D Converter for a 5mV/mA feedback signal.

APPLICATION NOTE 105: Current Sense Circuit Collection

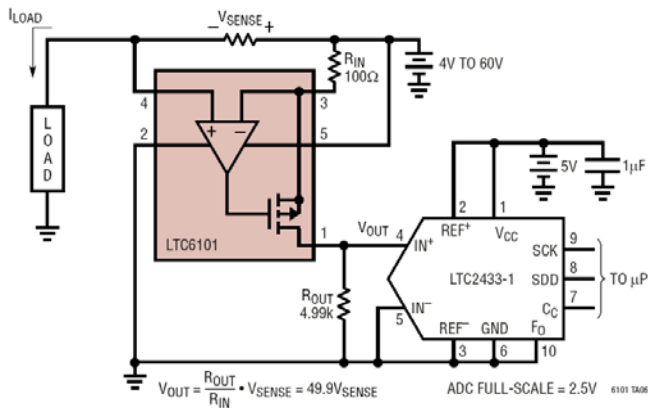
Split or Single Supply Operation, Bidirectional Output into A/D



In this circuit, split supply operation is used on both the LT1787 and LTC1404 to provide a symmetric bidirectional measurement. In the single-supply case, where the

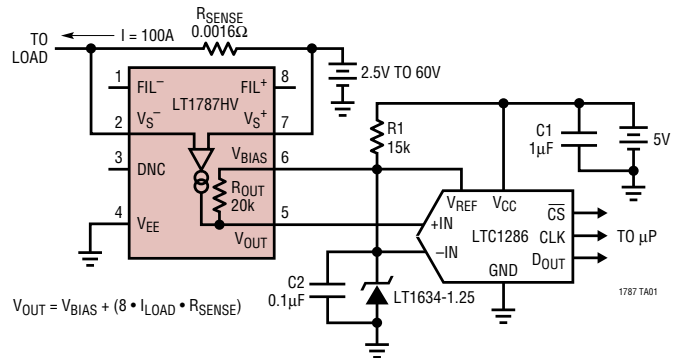
LT1787 pin 6 is driven by V_{REF} , the bidirectional measurement range is slightly asymmetric due to V_{REF} being somewhat greater than mid-span of the ADC input range.

16-Bit Resolution Unidirectional Output into LTC2433 ADC



The LTC2433-1 can accurately digitize signal with source impedances up to 5kΩ. This LTC6101 current sense circuit uses a 4.99kΩ output resistance to meet this requirement, thus no additional buffering is necessary.

12-Bit Resolution Unidirectional Output into LTC1286 ADC



While the LT1787 is able to provide a bidirectional output, in this application the economical LTC1286 is used to digitize a unidirectional measurement. The LT1787 has a nominal gain of eight, providing a 1.25V full-scale output at approximately 100A of load current.

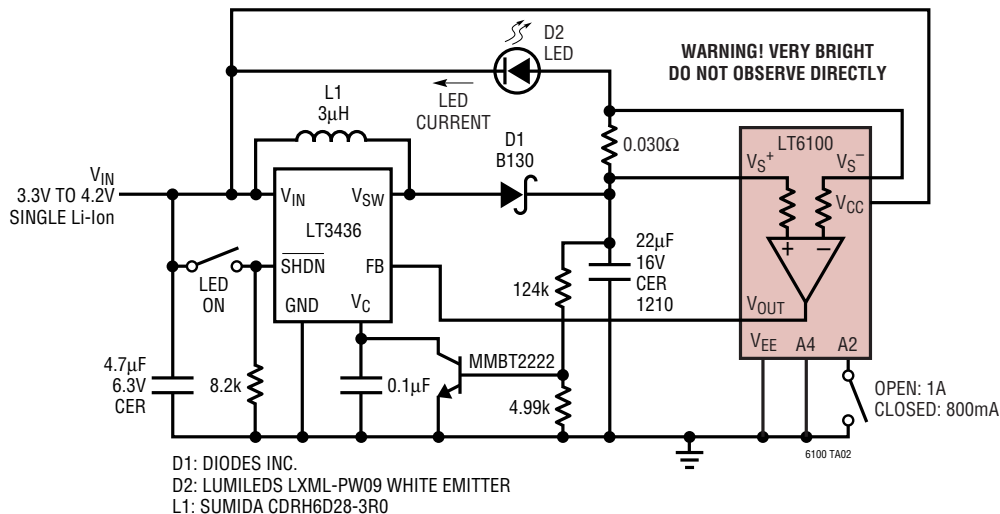
APPLICATION NOTE 105: Current Sense Circuit Collection

Current Control

This chapter collects a variety of techniques useful in generating controlled levels of current in circuits.

To see other chapters in this Application Note, return to the [Introduction](#).

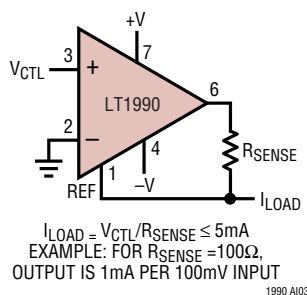
800 mA/1A White LED Current Regulator



The LT6100 is configured for a gain of either 40V/V or 50V/V depending on whether the switch between A2 and V_{EE} is closed or not. When the switch is open (LT6100 gain of 40V/V), 1A is delivered to the LED. When the switch is closed (LT6100 gain of 50V/V), 800mA is delivered.

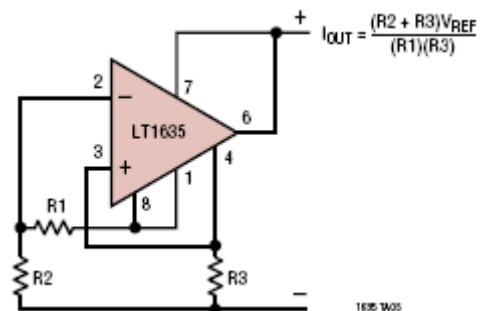
The LT3436 is a boost switching regulator which governs the voltage/current supplied to the LED. The switch “LED ON” connected to the SHDN pin allows for external control of the ON/OFF state of the LED.

Bidirectional Current Source



The LT1990 is a differential amplifier with integrated precision resistors. The circuit shown is the classic Howland current source, implemented by simply adding a sense resistor.

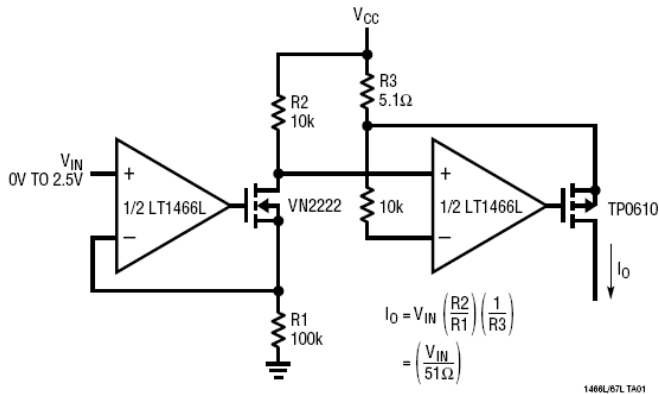
Two Terminal Current Regulator



The LT1635 combines an op amp with a 200mV reference. Scaling this reference voltage to a potential across resistor R3 forces a controlled amount of current to flow from the +terminal to the -terminal. Power is taken from the loop.

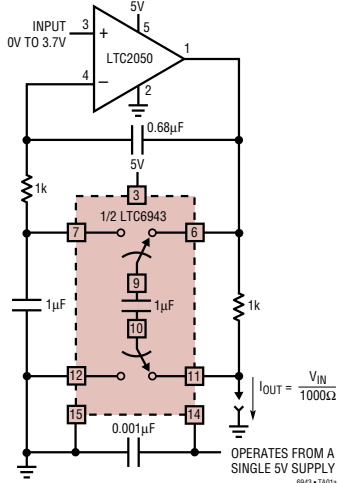
APPLICATION NOTE 105: Current Sense Circuit Collection

Variable Current Source



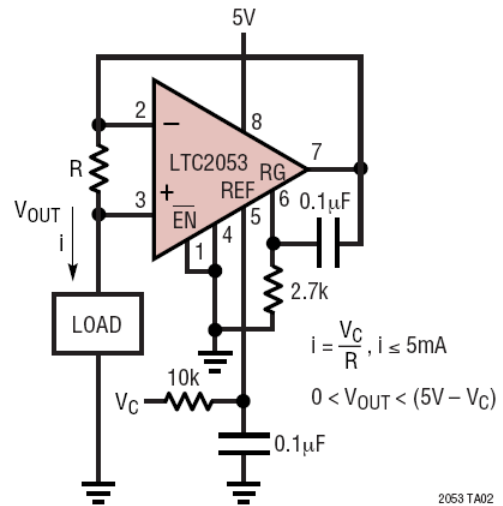
A basic high-side current source is implemented at the output, while an input translation amplifier section provides for flexible input scaling. A Rail-to-Rail input capability is required to have both amplifiers in one package, since the input stage has common-mode near ground and the second section operates near V_{CC} .

Precision Voltage Controlled Current Source with Ground Referred Input and Output



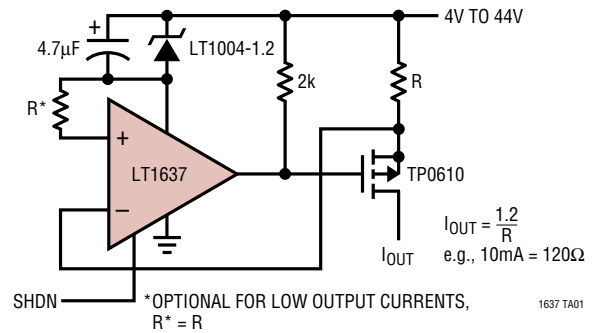
The LTC6943 is used to accurately sample the voltage across the 1kΩ sense resistor and translate it to a ground reference by charge balancing in the 1μF capacitors. The LTC2050 integrates the difference between the sense voltage and the input command voltage to drive the proper current into load.

Precision Voltage Controlled Current Source



The ultra-precise LTC2053 instrumentation amplifier is configured to servo the voltage drop on sense resistor R to match the command V_C . The LTC2053 output capability limits this basic configuration to low current applications.

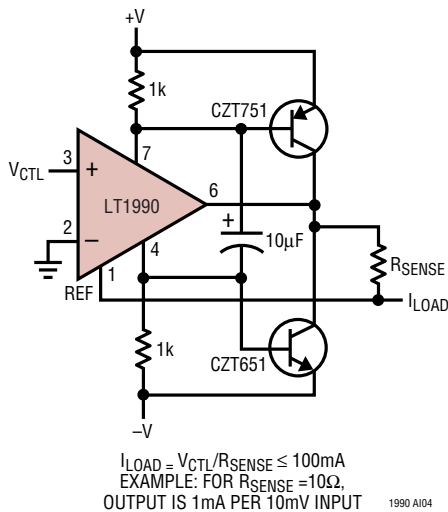
Switchable Precision Current Source



This is a simple current-source configuration where the op amp servos to establish a match between the drop on the sense resistor and that of the 1.2V reference. This particular op amp includes a shutdown feature so the current source function can be switched off with a logic command. The 2kΩ pull-up resistor assures the output MOSFET is off when the op amp is in shutdown mode.

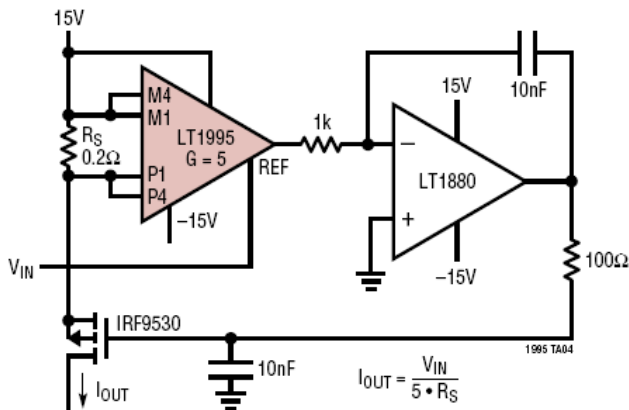
APPLICATION NOTE 105: Current Sense Circuit Collection

Boosted Bidirectional Controlled Current Source



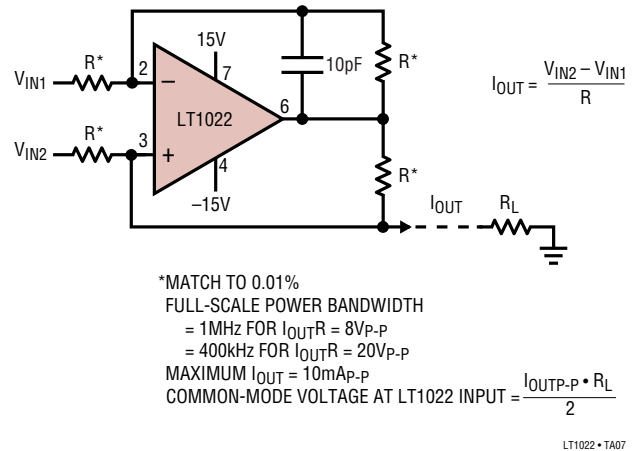
This is a classical Howland bidirectional current source implemented with an LT1990 integrated difference amplifier. The op amp circuit servos to match the RSENSE voltage drop to the input command VCTL. When the load current exceeds about 0.7mA in either direction, one of the boost transistors will start conducting to provide the additional commanded current.

0A to 2A Current Source



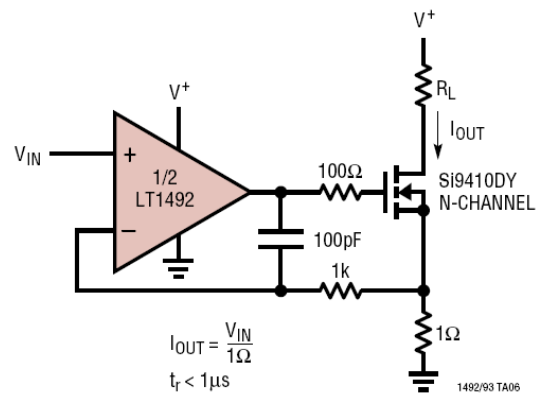
The LT1995 amplifies the sense resistor drop by 5V/V and subtracts that from V_{IN} , providing an error signal to an LT1880 integrator. The integrated error drives the PMOSFET as required to deliver the commanded current.

Fast Differential Current Source



This is a variation on the Howland configuration, where load current actually passes through a feedback resistor as an implicit sense resistance. Since the effective sense resistance is relatively large, this topology is appropriate for producing small controlled currents.

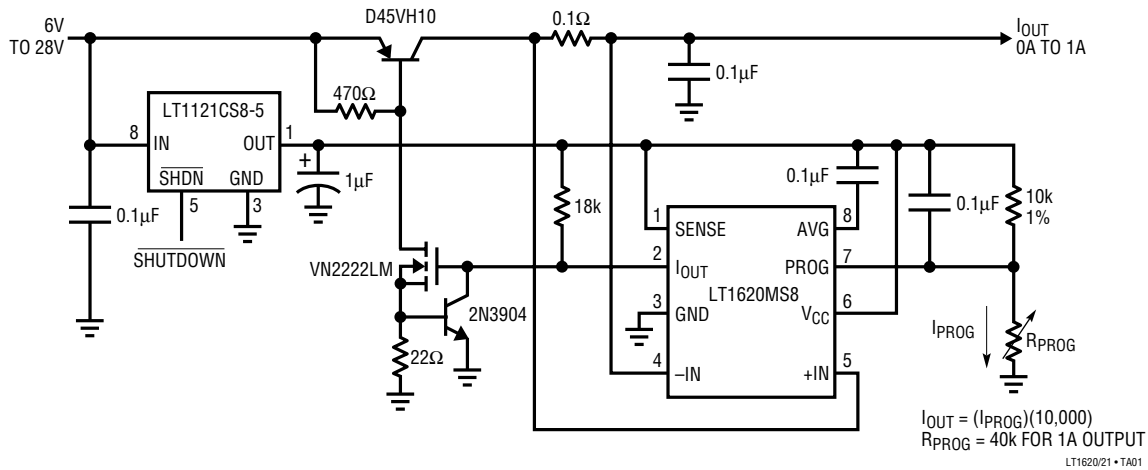
1A Voltage-Controlled Current Sink



This is a simple controlled current sink, where the op amp drives the NMOSFET gate to develop a match between the 1Ω sense resistor drop and the V_{IN} current command. Since the common-mode voltage seen by the op amp is near ground potential, a “single-supply” or Rail-to-Rail type is required in this application.

APPLICATION NOTE 105: Current Sense Circuit Collection

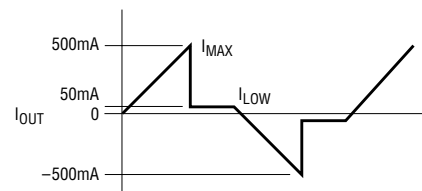
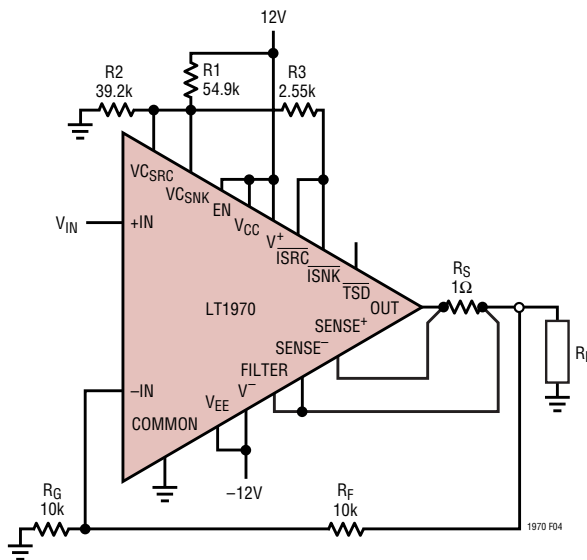
Programmable Constant Current Source



The current output can be controlled by a variable resistor (R_{PROG}) connected from the PROG pin to ground on the LT1620. The LT1121 is a low-dropout regulator that keeps the voltage constant for the LT1620. Applying a

shutdown command to the LT1121 powers down the LT1620 and eliminates the base-drive to the current regulation pass transistor, thereby turning off I_{OUT} .

Snap Back Current Limiting



$$I_{MAX} \approx \frac{V_{CC} \cdot R_2}{(R_1 + R_2) \cdot 10 \cdot R_S}$$

$$I_{LOW} \approx \frac{V_{CC} \cdot (R_2 || R_3)}{[R_1 + (R_2 || R_3)] \cdot 10 \cdot R_S}$$

The LT1970 provides current detection and limiting features built-in. In this circuit, the logic flags that are produced in a current-limiting event are connected in a feedback arrangement that in turn reduces the current limit

command to a lower level. When the load condition permits the current to drop below the limiting level, then the flags clear and full current drive capability is restored automatically.

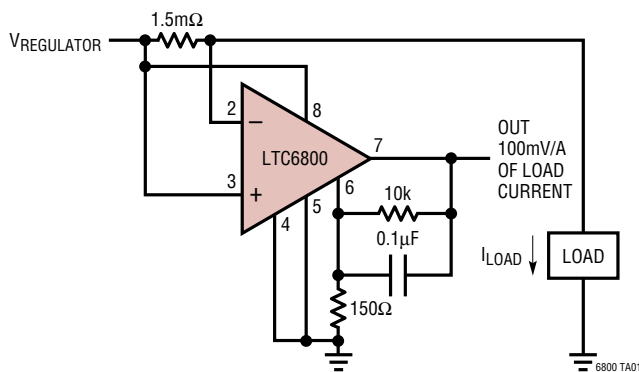
APPLICATION NOTE 105: Current Sense Circuit Collection

Precision

Offset voltage and bias current are the primary sources of error in current sensing applications. To maintain precision operation the use of zero-drift amplifier virtually eliminates the offset error terms.

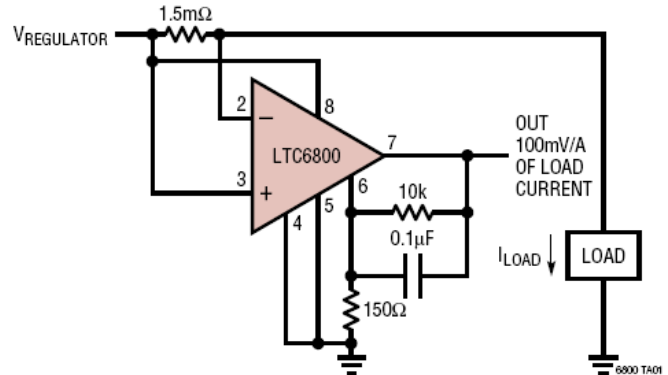
To see other chapters in this Application Note, return to the [Introduction](#).

Precision High Side Power Supply Current Sense



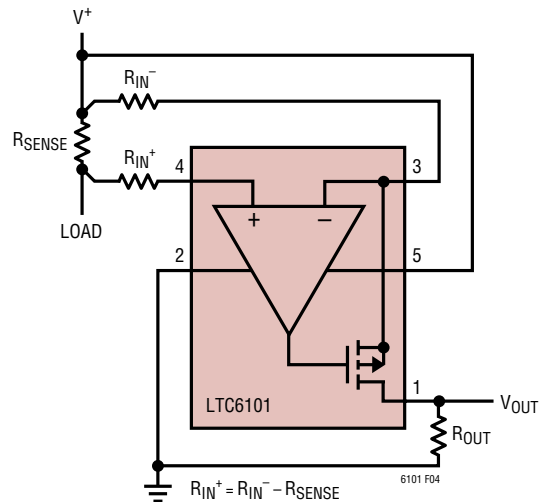
This is a low-voltage, ultra-high-precision monitor featuring a Zero-Drift Instrumentation Amplifier (IA) that provides Rail-to-Rail inputs and outputs. Voltage gain is set by the feedback resistors. Accuracy of this circuit is set by the quality of resistors selected by the user, small-signal range is limited by V_{OL} in single-supply operation. The voltage rating of this part restricts this solution to applications of $<5.5V$. This IA is sampled, so the output is discontinuous with input changes, thus only suited to very low frequency measurements.

High Side Power Supply Current Sense



The low offset error of the LTC6800 allows for unusually low sense resistance while retaining accuracy.

Second Input R Minimizes Error Due to Input Bias Current



The second input resistor decreases input error due caused by the input bias current. For smaller values of R_{IN} this may not be a significant consideration.

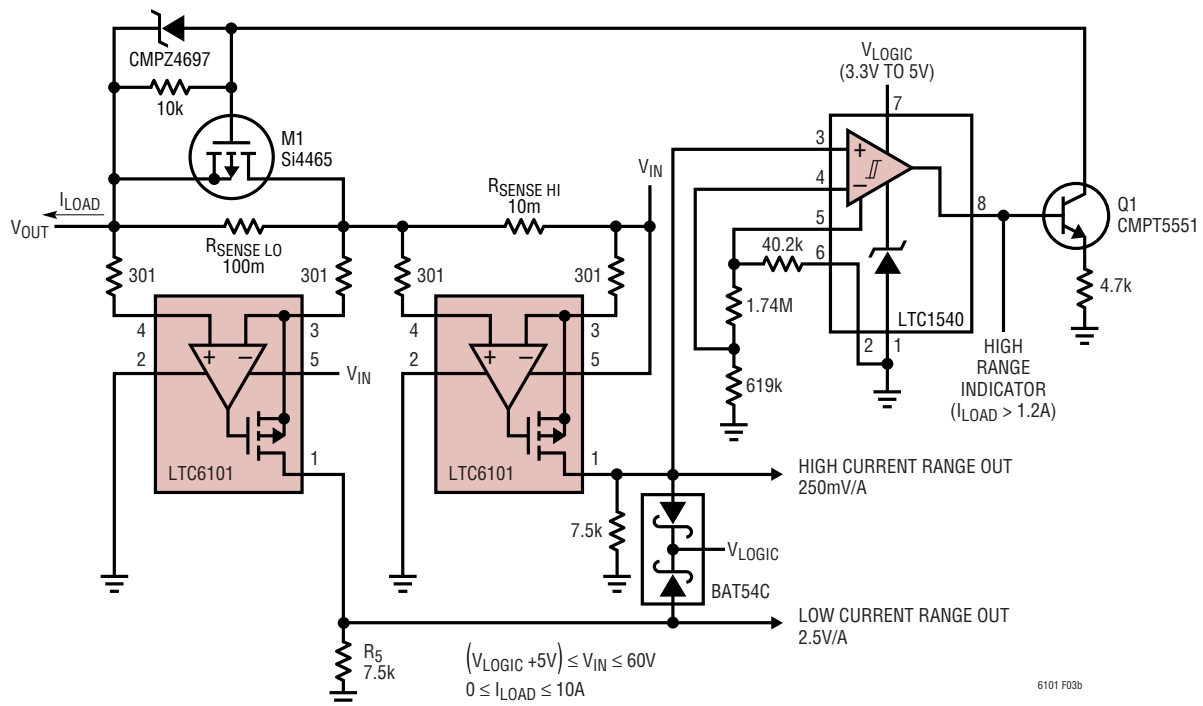
APPLICATION NOTE 105: Current Sense Circuit Collection

Wide Range

To measure current over a wide range of values requires gain changing in the current sense amplifier. This allows the use of a single value of sense resistor. The alternative approach is to switch values of sense resistor. Both approaches are viable for wide range current sensing.

To see other chapters in this Application Note, return to the [Introduction](#).

Dual LTC6101's Allow High-Low Current Ranging

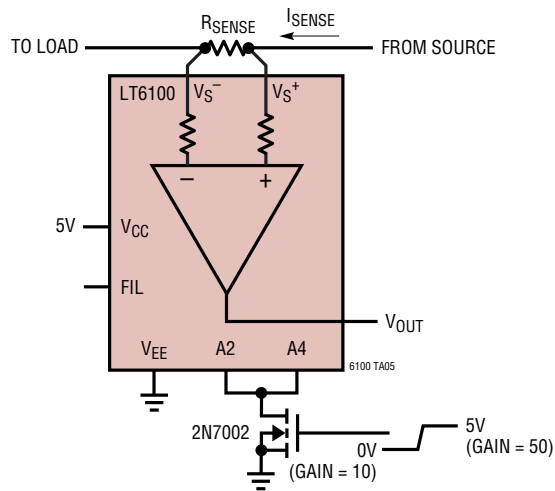


Using two current sense amplifiers with two values of sense resistors is an easy method of sensing current over a wide range. In this circuit the sensitivity and resolution of measurement is 10 times greater with low cur-

rents, less than 1.2 Amps, than with higher currents. A comparator detects higher current flow, up to 10 Amps, and switches sensing over to the high current circuitry.

APPLICATION NOTE 105: Current Sense Circuit Collection

Adjust Gain Dynamically for Enhanced Range



Instead of having fixed gains of 10, 12.5, 20, 25, 40, and 50, this circuit allows selecting between two gain settings. An NMOSFET switch is placed between the two gain-setting terminals (A2, A4) and ground to provide selection of gain = 10 or gain = 50, depending on the state of the gate drive. This provides a wider current measurement range than otherwise possible with just a single sense resistor.