Current Sense Circuit Collection

Making Sense of Current

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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. 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. To avoid duplication, circuits relevant to multiple chapters may appear in one location.

CIRCUIT COLLECTION INDEX

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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.

LOW SIDE CURRENT SENSING (Figure 1)

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

Figure 1. Low Side Current Sensing

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

HIGH SIDE CURRENT SENSING (Figure 2)

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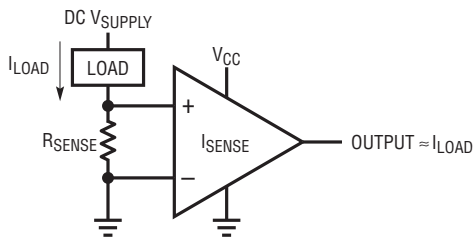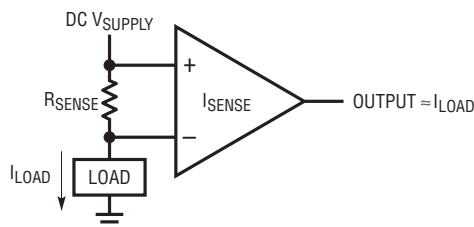

Figure 2. High Side Current Sensing

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

FULL-RANGE (HIGH AND LOW SIDE) CURRENT SENSING (Figure 3)

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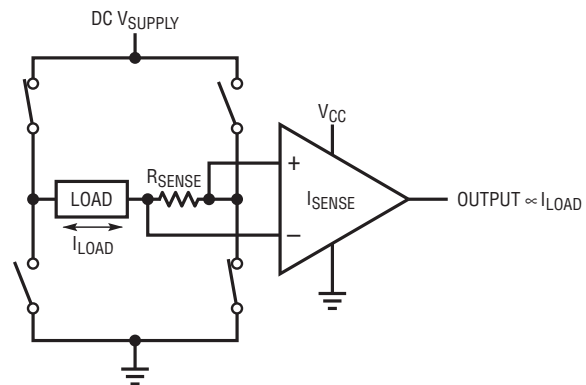

Figure 3. Full-Range (High And Low Side) Current Sensing

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

HIGH SIDE

Figure 7. Self-Powered High Side Current Sense

High Side Current Sense and Fuse Monitor (Figure 8)

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 1µA max from the battery bus.
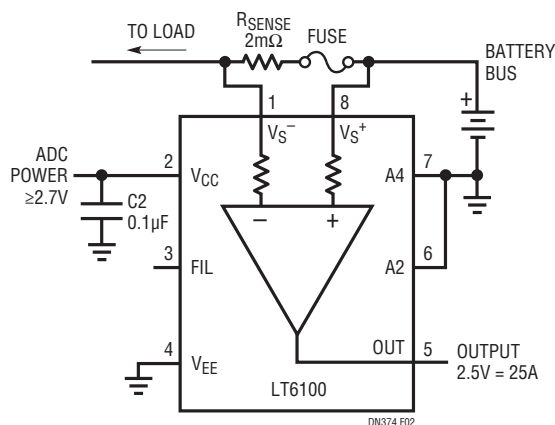
Figure 8. High Side Current Sense and Fuse Monitor

Precision High Side Power Supply Current Sense (Figure 9)

This is a low voltage, ultrahigh 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.
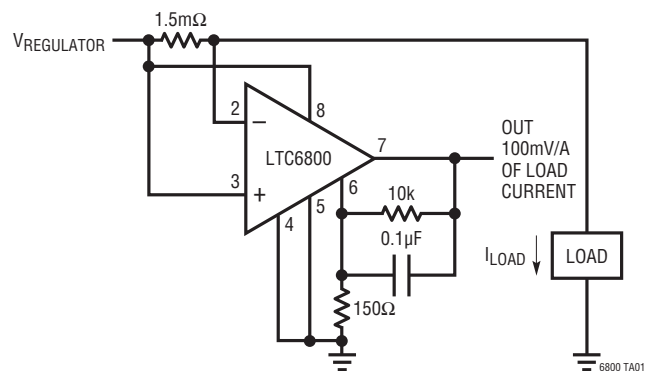
Figure 9. Precision High Side Power Supply Current Sense

Positive Supply Rail Current Sense (Figure 10)

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 R2 (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.

HIGH SIDE
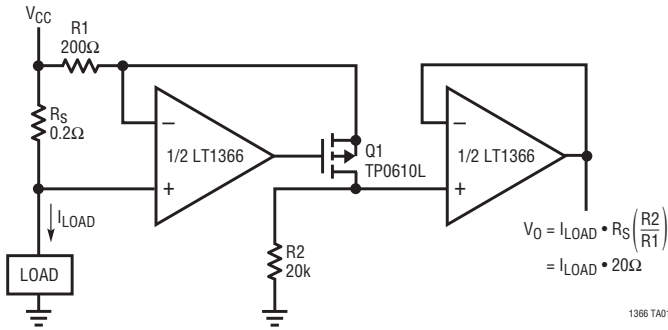
Figure 10. Positive Supply Rail Current Sense

$$V_O = I_{LOAD} \cdot R_S \left(\frac{R2}{R1} \right)$$
$$= I_{LOAD} \cdot 20\Omega$$

Precision Current Sensing in Supply Rails (Figure 11)

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 ultrahigh 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.

Figure 11. Precision Current Sensing in Supply Rails

Measuring Bias Current Into an Avalanche Photo Diode (APD) Using an Instrumentation Amplifier (Figures 12a and 12b)

The upper circuit (a) uses an instrumentation amplifier (IA) powered by a separate rail (>1V above V_{IN}) to measure across the 1kΩ current shunt. The lower figure (b) 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.
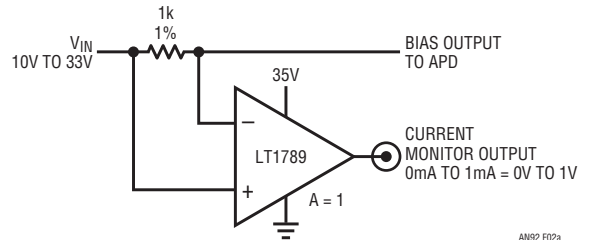
Figure 12a
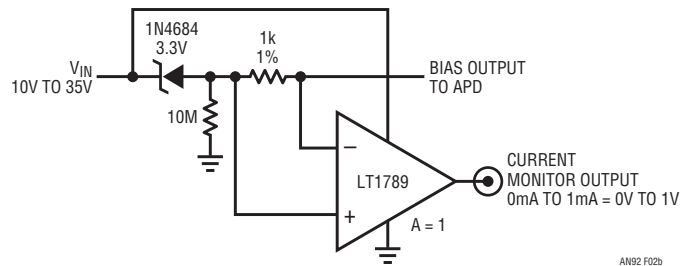
Figure 12b

Figure 12. Measuring Bias Current Into an Avalanche Photo Diode (APD) Using an Instrumentation Amplifier

HIGH SIDE

Simple 500V Current Monitor (Figure 13)

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 (Figure 14)

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.

DANGER! Lethal Potentials Present — Use Caution

$$V_{OUT} = \frac{R_{OUT}}{R_{IN}} \cdot V_{SENSE} = 49.9\ V_{SENSE}$$

M1 AND M2 ARE FQD3P50 TM

Figure 13. Simple 500V Current Monitor

Figure 14. Bidirectional Battery-Current Monitor

HIGH SIDE

LTC6101 Supply Current Included as Load in Measurement (Figure 15)

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.
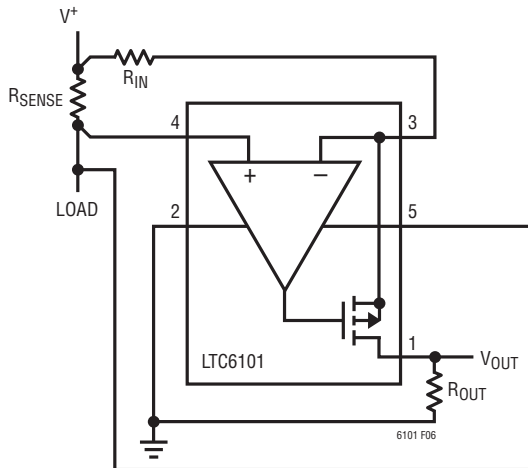
Figure 15. LTC6101 Supply Current Included as Load in Measurement

Simple High Side Current Sense Using the LTC6101 (Figure 16)

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 1µs 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 250µA supply current when the load is off.

Figure 16. Simple High Side Current Sense Using the LTC6101

High Side Transimpedance Amplifier (Figure 17)

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.
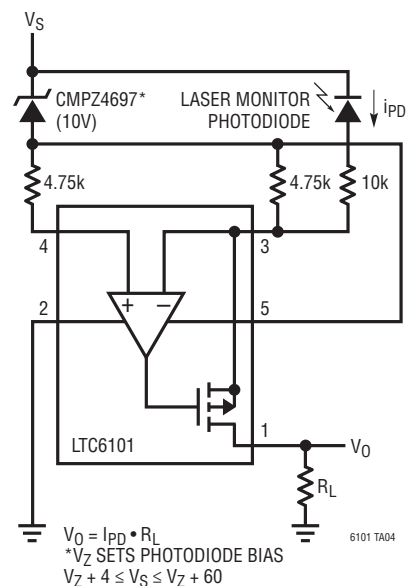
Figure 17. High Side Transimpedance Amplifier

HIGH SIDE

Intelligent High Side Switch (Figure 18)

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 (Figure 19)

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.

N = OPTO-ISOLATOR CURRENT GAIN

$$V_{OUT} = V_{LOGIC} - I_{SENSE} \cdot \frac{R_{SENSE}}{R_{IN}} \cdot N \cdot R_{OUT}$$

6101 TA08
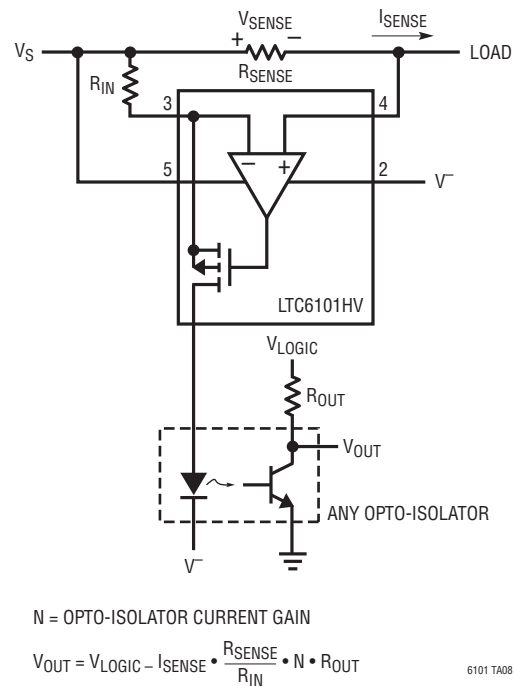
Figure 19. 48V Supply Current Monitor with Isolated Output and 105V Survivability

$V_O = 49.9 \cdot R_S \cdot I_L$

FOR $R_S = 5m\Omega$,
$V_O = 2.5V$ AT $I_L = 10A$ (FULL-SCALE)

6101 TA07
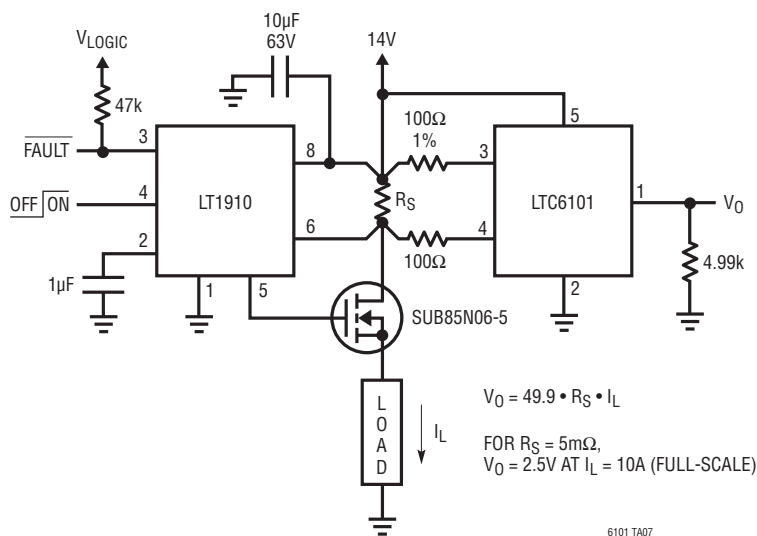
Figure 18. Intelligent High Side Switch

HIGH SIDE

Precision, Wide Dynamic Range High Side Current Sensing (Figure 20)

The LTC6102 offers exceptionally high precision ($V_{OS} <$ 10µV) so that a low value sense resistor may be used. This reduces dissipation in the circuit and allows wider variations in current to be accurately measured. In this circuit, the components are scaled for a 10A measuring range, with the offset error corresponding to less than 10mA. This is effectively better than 10-bit dynamic range with dissipation under 100mW.

Sensed Current Includes Monitor Circuit Supply Current (Figure 21)

To sense all current drawn from a battery power source which is also powering the sensing circuitry requires the proper connection of the supply pin. Connecting the supply pin to the load side of the sense resistor adds the supply current to the load current. The sense amplifier operates properly with the inputs equal to the device V^+ supply.

$$V_{OUT} = \frac{R_{OUT}}{R_{IN}} \cdot V_{SENSE} = 249.5V_{SENSE}$$

*PROPER SHUNT SELECTION COULD ALLOW MONITORING OF CURRENTS IN EXCESS OF 1000A

Figure 20. Precision, Wide Dynamic Range High Side Current Sensing

$$V_{OUT} = 49.9 \cdot R_{SENSE} (I_{LOAD} + I_{SUPPLY})$$
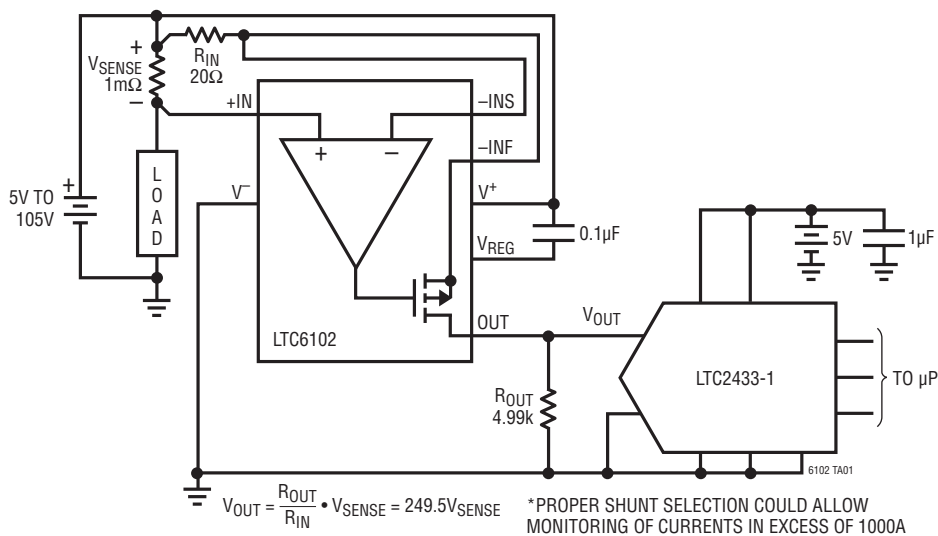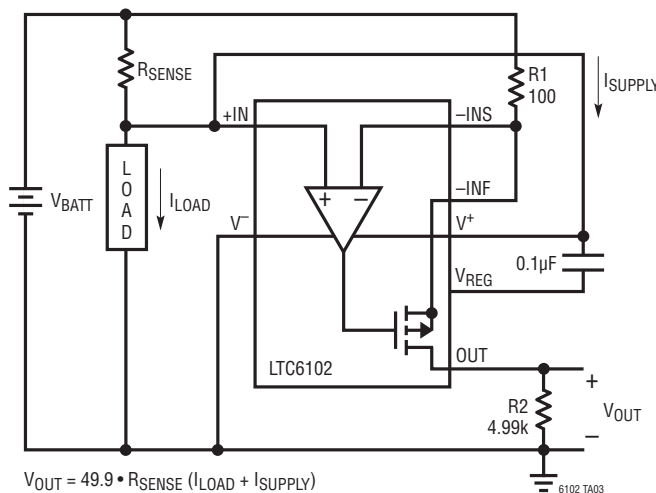
Figure 21. Sensed Current Includes Monitor Circuit Supply Current

HIGH SIDE

Wide Voltage Range Current Sensing (Figure 22)

The LT6105 has a supply voltage that is independent from the potential at the current sense inputs. The input voltage can extend below ground or exceed the sense amplifier supply voltage. While the sensed current must flow in just one direction, it can be sensed above the load, high side, or below the load, low side. Gain is programmed through resistor scaling and is set to 50 in the circuit shown.

Smooth Current Monitor Output Signal by Simple Filtering (Figure 23)

The output impedance of the LT6105 amplifier is defined by the value of the gain setting output resistor. Bypassing this resistor with a single capacitor provides first order filtering to smooth noisy current signals and spikes.

$$V_{OUT} = (V_S^+ - V_S^-) \bullet \frac{R_{OUT}}{R_{IN}}; \quad A_V = \frac{R_{OUT}}{R_{IN}}; \quad R_{IN1} = R_{IN2} = R_{IN}$$
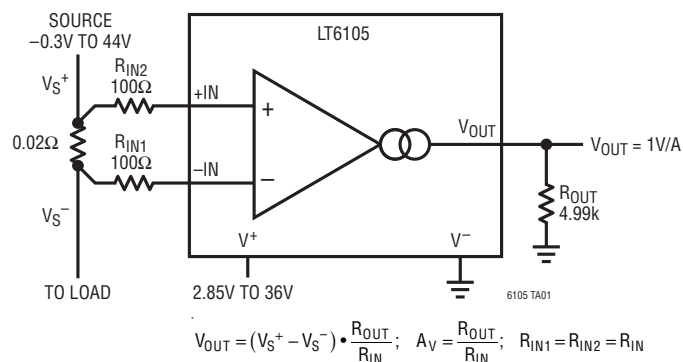
Figure 22. Wide Voltage Range Current Sensing
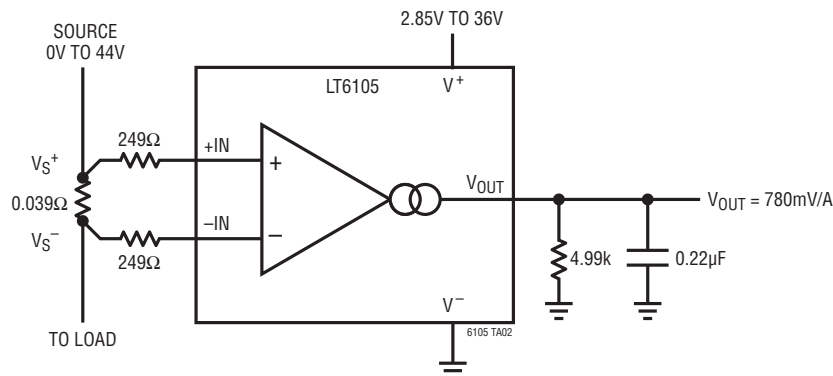
Figure 23. Smooth Current Monitor Output Signal by Simple Filtering

HIGH SIDE

Power on Reset Pulse Using a TimerBlox Device (Figure 24)

When power is first applied to a system the load current may require some time to rise to the normal operating level. This can trigger and latch the LT6109 comparator monitoring undercurrent conditions. After a known start-up time delay interval, R7 and C1 create a falling edge to trigger an LTC6993-3 one-shot programmed for 10µs. This pulse unlatches the comparators. R8 and Q2 will discharge C1 on loss of the supply to ensure that a full delay interval occurs when power returns.
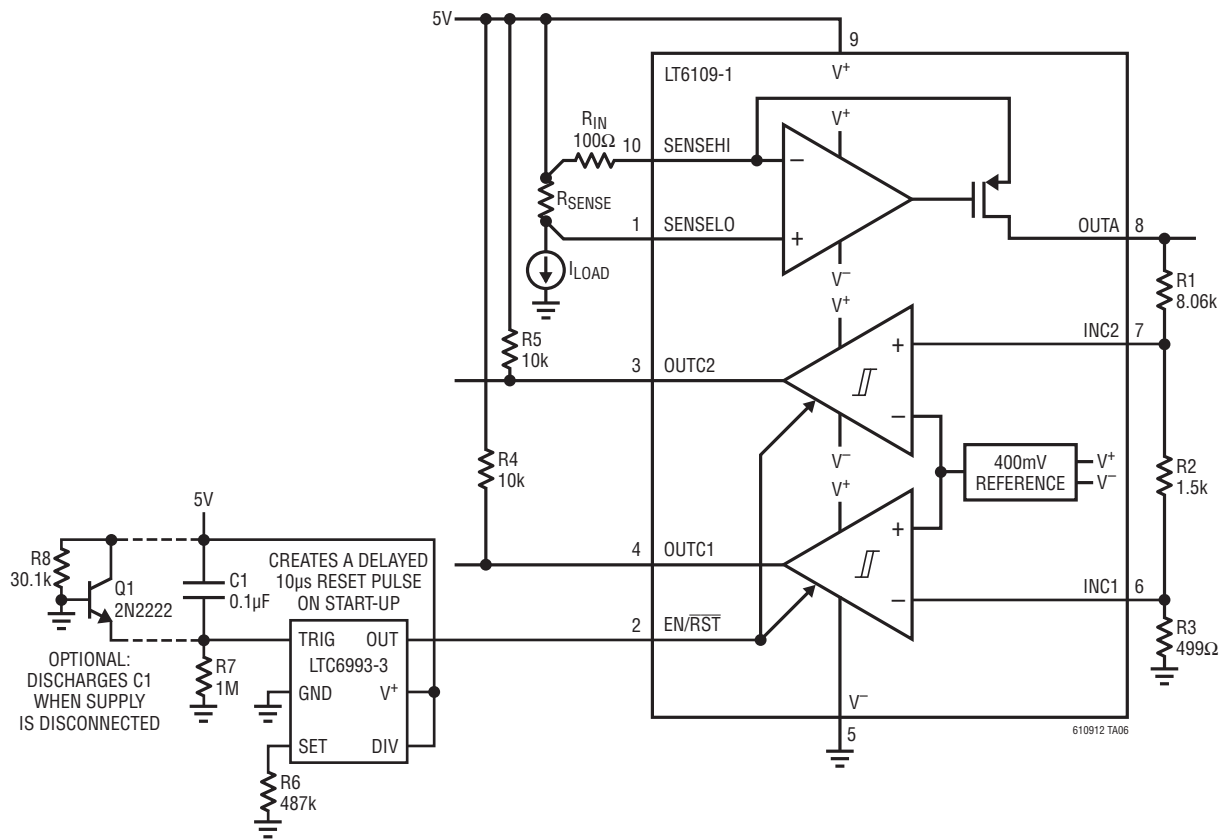
Figure 24. Power on Reset Pulse Using a TimerBlox Device

HIGH SIDE

Accurate Delayed Power on Reset Pulse Using TimerBlox Devices (Figure 25)

When power is first applied to a system the load current may require some time to rise to the normal operating level. This can trigger and latch the LT6109 comparator monitoring undercurrent conditions. In this circuit an

LTC6994-1 delay timer is used to set an interval longer than the known time for the load current to settle (1 second in the example) then triggers an LTC6993-3 one-shot programmed for 10µs. This pulse unlatches the comparators. The power-on delay time is resistor programmable over a wide range.

Figure 25. Accurate Delayed Power on Reset Pulse Using TimerBlox Devices

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HIGH SIDE

More High Side Circuits Are Shown in Other Chapters:

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HIGH SIDE

More High Side Circuits Are Shown in Other Chapters:

FIGURE	TITLE
188	Power over Ethernet, PoE, Monitoring
189	Monitor Current, Voltage and Temperature
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209	Use Kelvin Connections to Maintain High Current Accuracy
210	Crystal/Reference Oven Controller
211	Power Intensive Circuit Board Monitoring
212	Crystal/Reference Oven Controller
215	0 to 10A Sensing Over Two Ranges
216	Dual Sense Amplifier Can Have Different Sense Resistors and Gain

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.

"Classic" High Precision Low Side Current Sense (Figure 26)

This configuration is basically a standard noninverting 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.
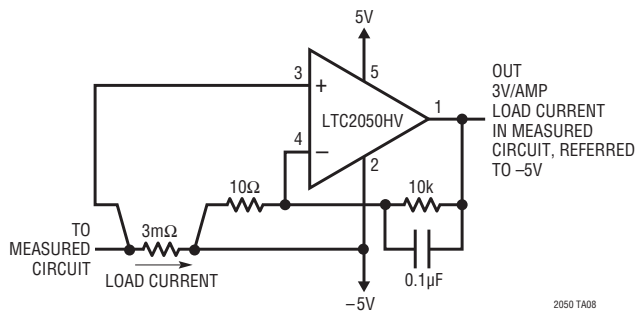
Figure 26. "Classic" High Precision Low Side Current Sense

Precision Current Sensing in Supply Rails (Figure 27)

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 ultrahigh 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.

Figure 27. Precision Current Sensing in Supply Rails

LOW SIDE

–48V Hot Swap Controller (Figure 28)

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 (Figure 29)

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 transimpedance 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.

Figure 28.–48V Hot Swap Controller
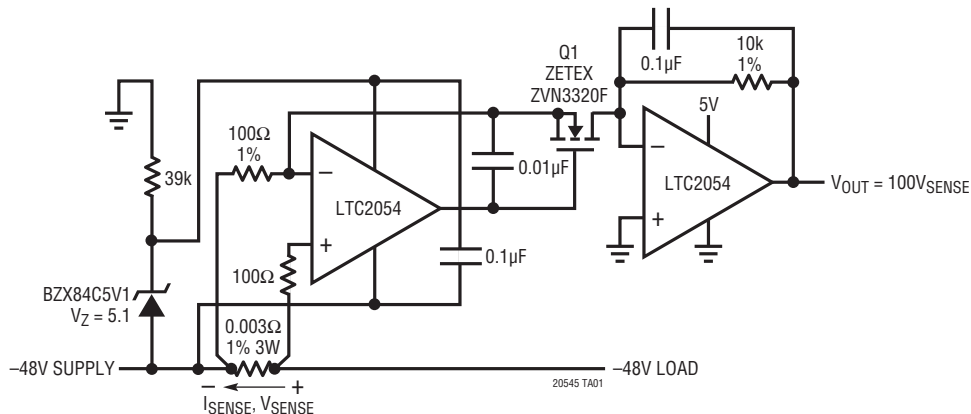
Figure 29.–48V Low Side Precision Current Sense

LOW SIDE

Fast Compact –48V Current Sense (Figure 30)

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 (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 (Figures 31a and 31b)

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 in Figure 31b. For complete dielectric isolation and/or higher efficiency operation, the ADC may be powered from a small transformer circuit as shown in Figure 31b.

Figure 30. Fast Compact –48V Current Sense

Figure 31a

Figure 31b

Figure 31. –48V Current Monitor

LOW SIDE

–48V Hot Swap Controller (Figure 32)

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.

Simple Telecom Power Supply Fuse Monitor (Figure 33)

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.
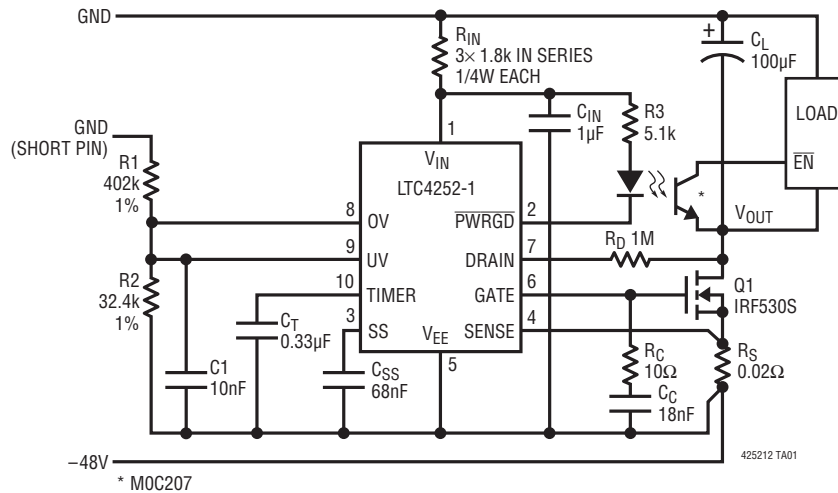
Figure 32.–48V Hot Swap Controller

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

Figure 33. Simple Telecom Power Supply Fuse Monitor

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LOW SIDE

More Low Side Circuits Are Shown in Other Chapters:

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23	Smooth Current Monitor Output Signal by Simple Filtering
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122	Monitor Solenoid Current on the Low Side
127	Monitor both the ON Current and the Freewheeling Current In a Low Side Driven Solenoid
168	Monitoring a Fuse Protected Circuit

NEGATIVE VOLTAGE

This chapter discusses solutions for negative voltage current sensing.

Telecom Supply Current Monitor (Figure 34)

The LT1990 is a wide common mode range difference amplifier used here to amplify the sense resistor drop by ten. To provide the desired input range when using a single 5V supply, the reference potential is set to approximately 4V by the LT6650. The output signal moves downward from the reference potential in this connection so that a large output swing can be accommodated.

–48V Hot Swap Controller (Figure 35)

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.

Figure 34. Telecom Supply Current Monitor

Figure 35.–48V Hot Swap Controller

NEGATIVE VOLTAGE

–48V Low Side Precision Current Sense (Figure 36)

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 transimpedance 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 (Figure 37)

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 (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.
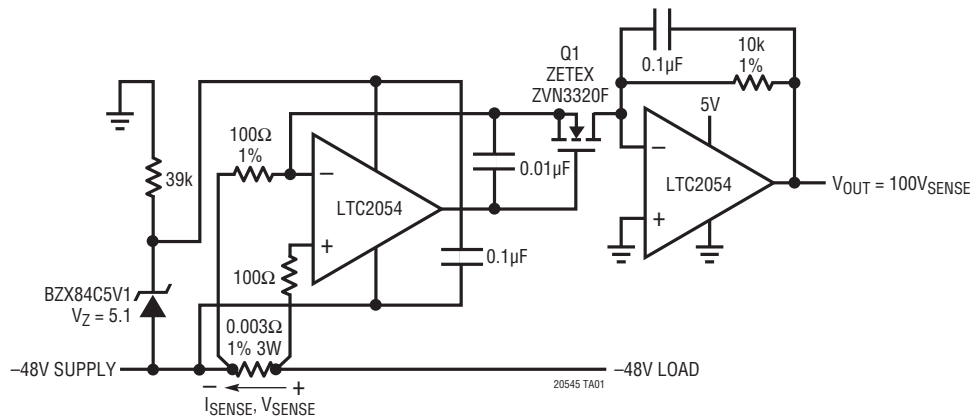
Figure 36. –48V Low Side Precision Current Sense
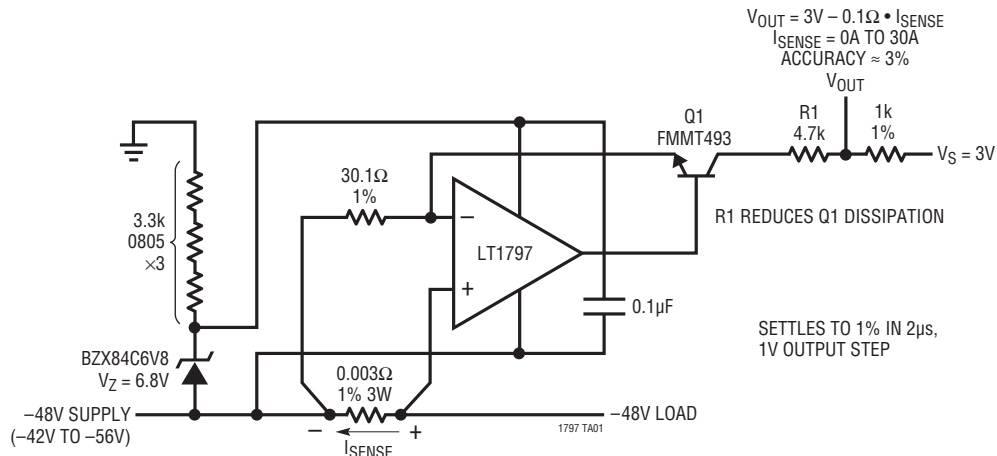
Figure 37. Fast Compact –48V Current Sense

NEGATIVE VOLTAGE

–48V Current Monitor (Figures 38a and 38b)

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 in Figure 38b.

Simple Telecom Power Supply Fuse Monitor (Figure 39)

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.
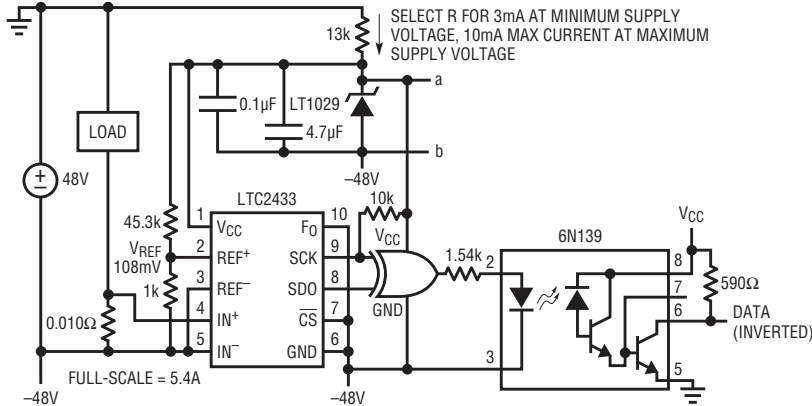
Figure 38b

Figure 38a

Figure 38. –48V Current Monitor

VA	VB	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

VFUSE A	VFUSE B	FUSE STATUS
= VA	= VB	0
= VA	≠ VB	1
≠ VA	= VB	1
≠ VA	≠ VB	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
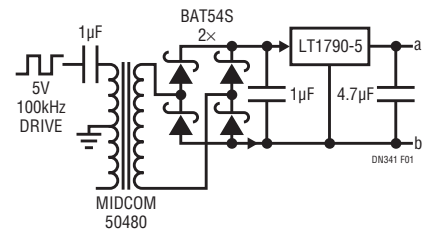
Figure 39. Simple Telecom Power Supply Fuse Monitor

an105fa

NEGATIVE VOLTAGE

Monitor Current in Positive or Negative Supply Lines (Figure 40)

Using a negative supply voltage to power the LT6105 creates a circuit that can be used to monitor the supply current in a positive or negative supply line by only changing the input connections. In both configurations the output is a ground referred positive voltage. The negative supply to the LT6105 must be at least as negative as the supply line it is monitoring.
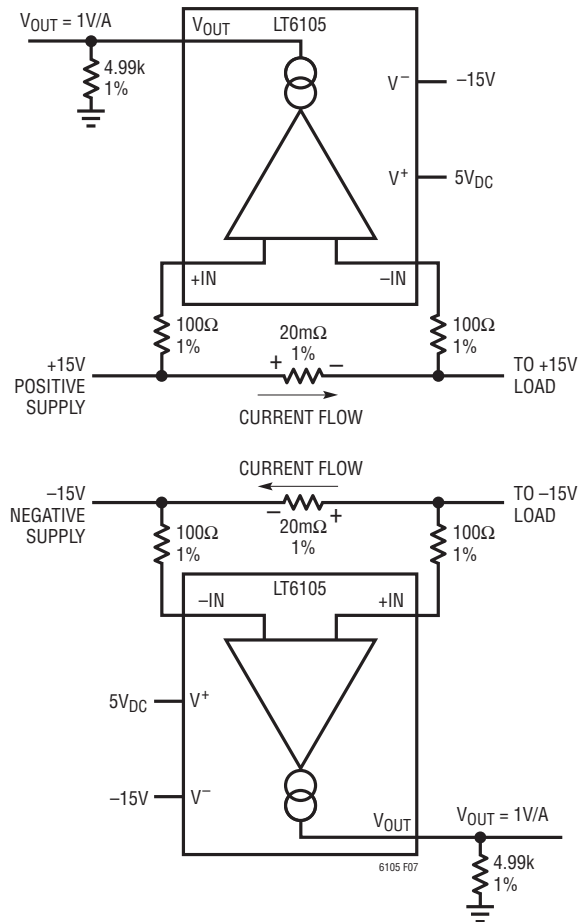
Figure 40. Monitor Current in Positive or Negative Supply Lines

UNIDIRECTIONAL

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

Unidirectional Output into A/D with Fixed Supply at V_S^+ (Figure 41)

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 R1 and R2. This voltage increases as sense current increases, with the amplified sense voltage appearing between the A/D converters –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.
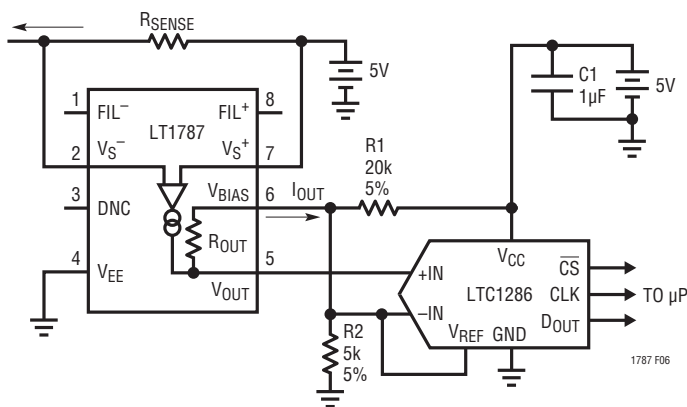
Figure 41. Unidirectional Output into A/D with Fixed Supply at V_S^+

Unidirectional Current Sensing Mode (Figures 42a and 42b)

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}.
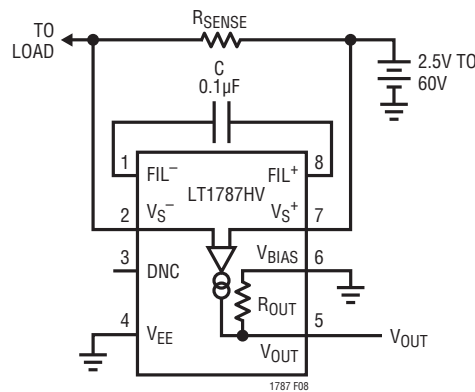
Figure 42a
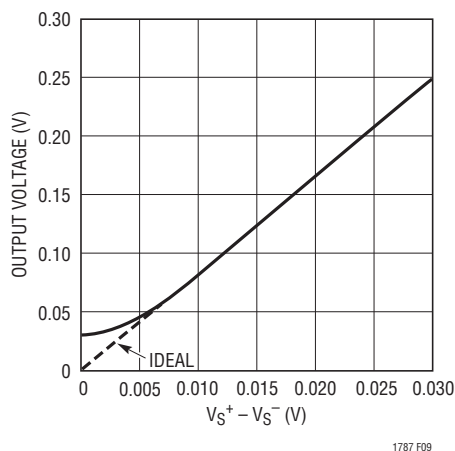
Figure 42b

Figure 42. Unidirectional Current Sensing Mode

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UNIDIRECTIONAL

16-Bit Resolution Unidirectional Output into LTC2433 ADC (Figure 43)

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 (Figure 44)

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.

$$V_{OUT} = \frac{R_{OUT}}{R_{IN}} \cdot V_{SENSE} = 49.9 V_{SENSE}$$

ADC FULL-SCALE = 2.5V
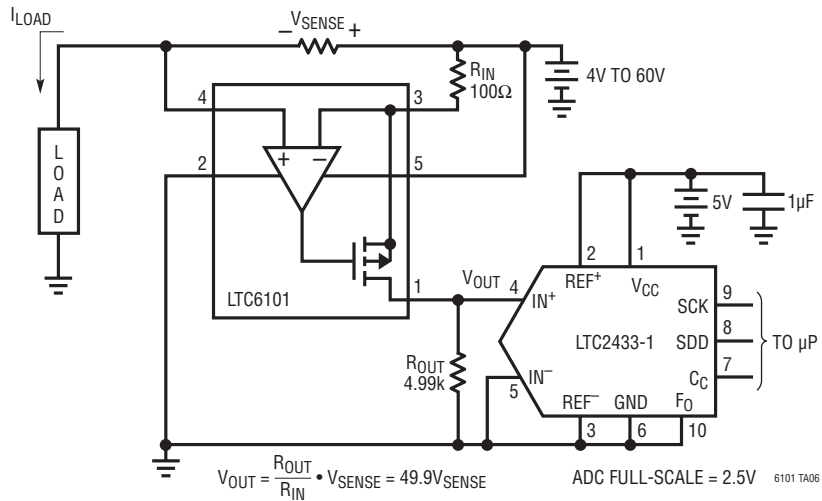
Figure 43. 16-Bit Resolution Unidirectional Output into LTC2433 ADC

$V_O = 49.9 \cdot R_S \cdot I_L$

FOR $R_S = 5m\Omega$,
$V_O = 2.5V$ AT $I_L = 10A$ (FULL-SCALE)
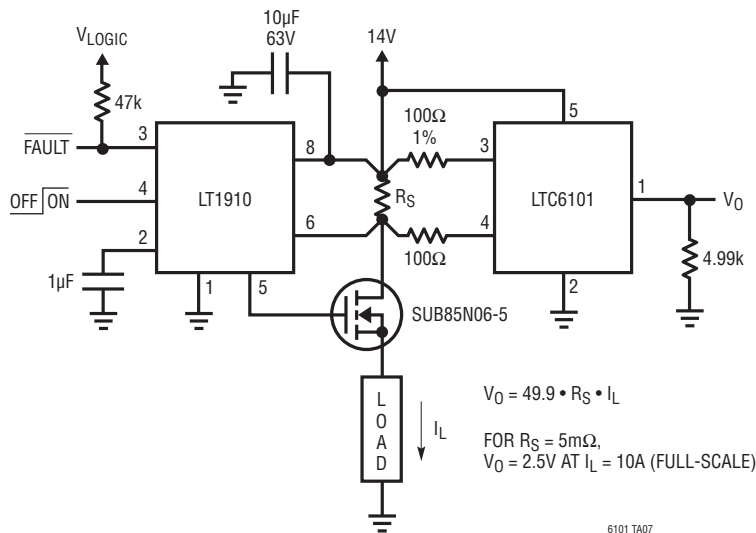
Figure 44. Intelligent High Side Switch

UNIDIRECTIONAL

48V Supply Current Monitor with Isolated Output and 105V Survivability (Figure 45)

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 (Figure 46)

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.

N = OPTO-ISOLATOR CURRENT GAIN

$$V_{OUT} = V_{LOGIC} - I_{SENSE} \bullet \frac{R_{SENSE}}{R_{IN}} \bullet N \bullet R_{OUT}$$

6101 TA08
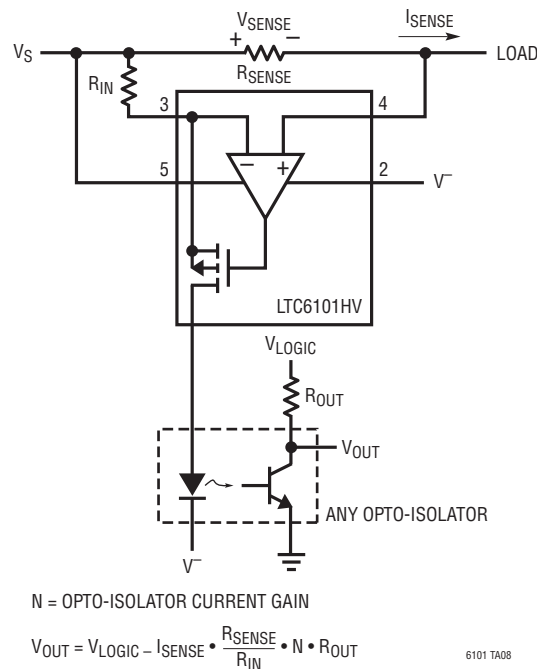
Figure 45. 48V Supply Current Monitor with Isolated Output and 105V Survivability

$$V_{OUT} = V_{BIAS} + (8 \bullet I_{LOAD} \bullet R_{SENSE})$$

1787 TA01

Figure 46. 12-Bit Resolution Unidirectional Output into LTC1286 ADC

UNIDIRECTIONAL

More Unidirectional Circuits Are Shown in Other Chapters:

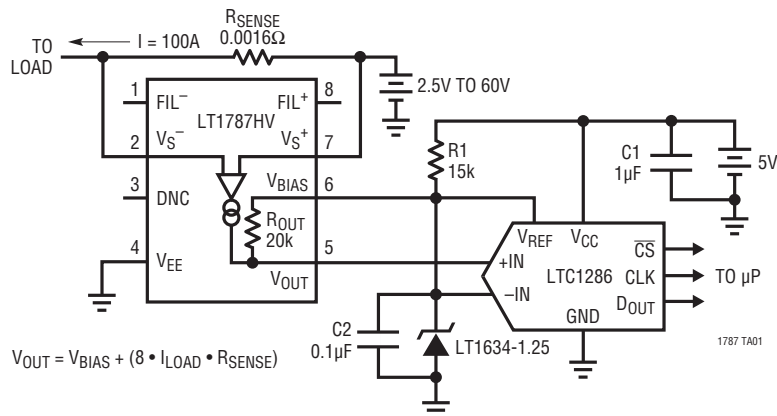| FIGURE	TITLE
20	Precision, Wide Dynamic Range High-side Current Sensing
21	Sensed Current Includes Monitor Circuit Supply Current
22	Wide Voltage Range Current Sensing
23	Smooth Current Monitor Output Signal by Simple Filtering
24	Power on Reset Pulse Using a TimerBlox Device
25	Accurate Delayed Power on Reset Pulse Using TimerBlox Devices
40	Monitor Current in Positive or Negative Supply Lines
93	High Voltage Current and Temperature Monitoring
104	Using Printed Circuit Sense Resistance
105	High Voltage, 5A High Side Current Sensing in Small Package
121	Single Output Provides 10A H-Bridge Current and Direction
122	Monitor Solenoid Current on the Low Side
123	Monitor Solenoid Current on the High Side
125	Large Input Voltage Range for Fused Solenoid Current Monitoring
126	Monitor both the ON Current and the Freewheeling Current Through a High Side Driven Solenoid
127	Monitor both the ON Current and the Freewheeling Current In a Low Side Driven Solenoid
129	Simple DC Motor Torque Control
130	Small Motor Protection and Control
131	Large Motor Protection and Control
143	Battery Stack Monitoring
148	Complete Single Cell Battery Protection
167	Monitor Current in an Isolated Supply Line
168	Monitoring a Fuse Protected Circuit
169	Circuit Fault Protection with Early Warning and Latching Load Disconnect
170	Use Comparator Output to Initialize Interrupt Routines
171	Current Sense with Over-current Latch and Power-On Reset with Loss of Supply
176	Directly Digitize Current with 16-Bit Resolution
177	Directly Digitizing Two Independent Currents
180	Complete Digital Current Monitoring
182	Power Sensing with Built In A to D Converter
183	Isolated Power Measurement
184	Fast Data Rate Isolated Power Measurement
185	Adding Temperature Measurement to Supply Power Measurement
186	Current, Voltage and Fuse Monitoring
187	Automotive Socket Power Monitoring
188	Power over Ethernet, PoE, Monitoring
189	Monitor Current, Voltage and Temperature
208	Remote Current Sensing with Minimal Wiring

UNIDIRECTIONAL

More Unidirectional Circuits Are Shown in Other Chapters:

BIDIRECTIONAL

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

Bidirectional Current Sensing with Single-Ended Output (Figure 47)

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.

2.5V TO 5V (CONNECTION A)
2.5V TO 0V (CONNECTION B)
0A TO 1A IN EITHER DIRECTION
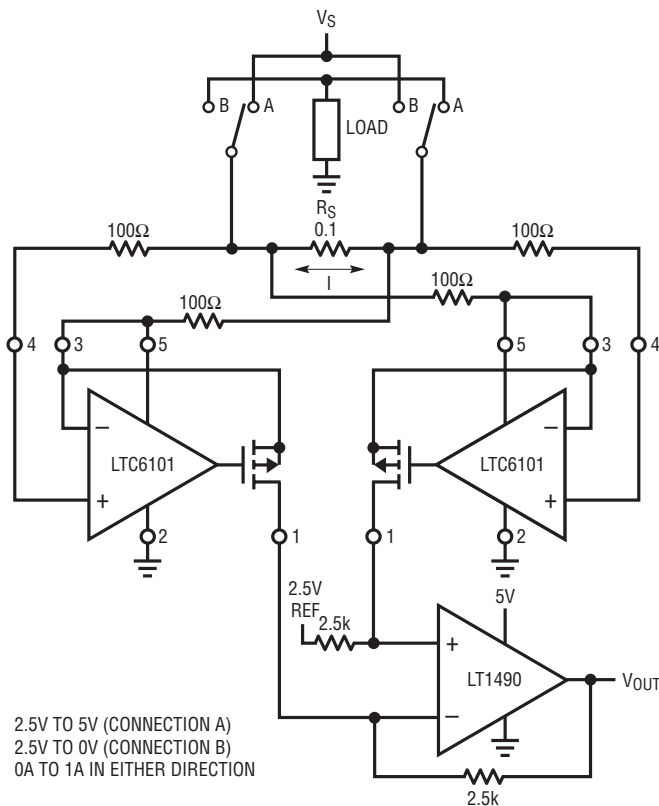
Figure 47. Bidirectional Current Sensing with Single-Ended Output

Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information (Figure 48)

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.
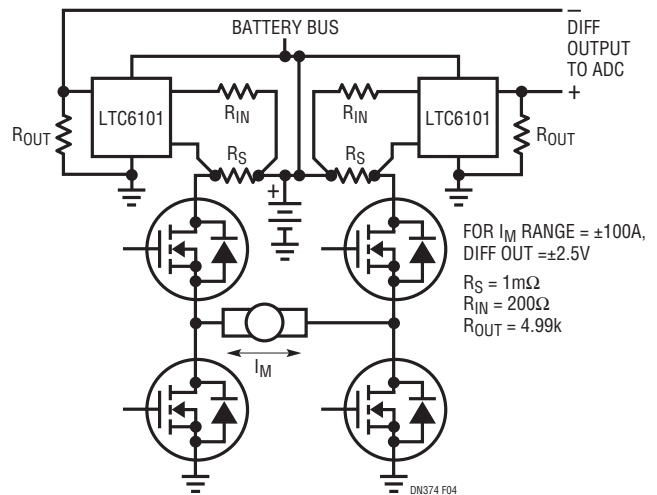

FOR I_M RANGE = ±100A,
DIFF OUT =±2.5V

R_S = 1mΩ
R_{IN} = 200Ω
R_{OUT} = 4.99k

Figure 48. Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information

BIDIRECTIONAL

Conventional H-Bridge Current Monitor (Figure 49)

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 (Figure 50)

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 noninverting 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.
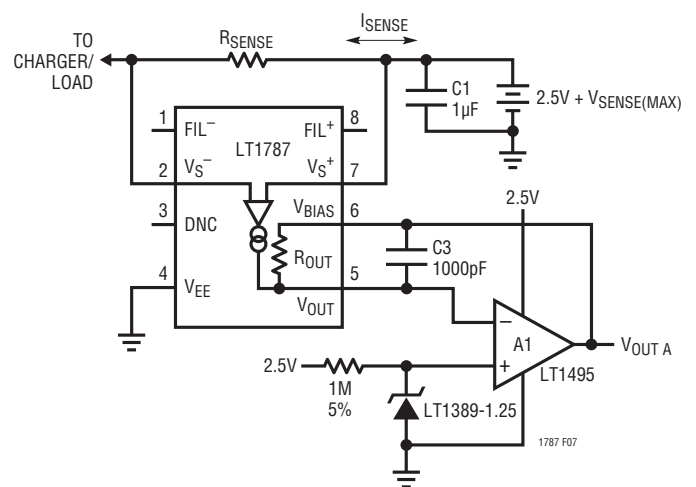
Figure 50. Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter

Figure 49. Conventional H-Bridge Current Monitor

BIDIRECTIONAL

Battery Current Monitor (Figure 51)

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.

$$V_O = I_L \left(\frac{R_B}{R_A} \right) R_{SENSE}$$

FOR $R_A = 1k$, $R_B = 10k$

$$\frac{V_O}{I_L} = 1V/A$$
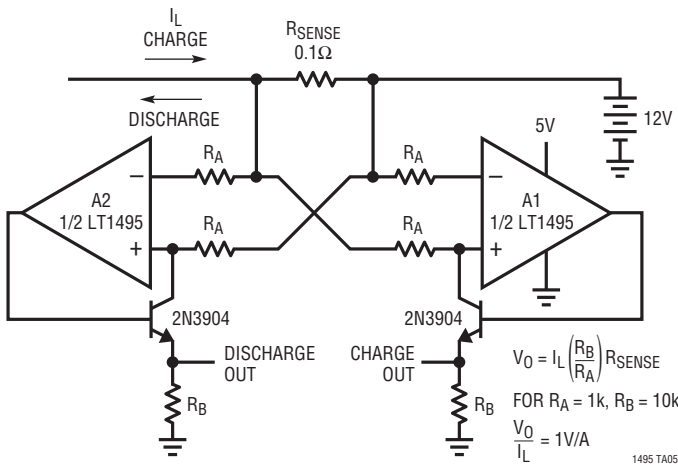
Figure 51. Battery Current Monitor

Fast Current Sense with Alarm (Figure 52)

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/µs 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 overcurrent flag. With the 400mV reference the flag occurs at 4A.
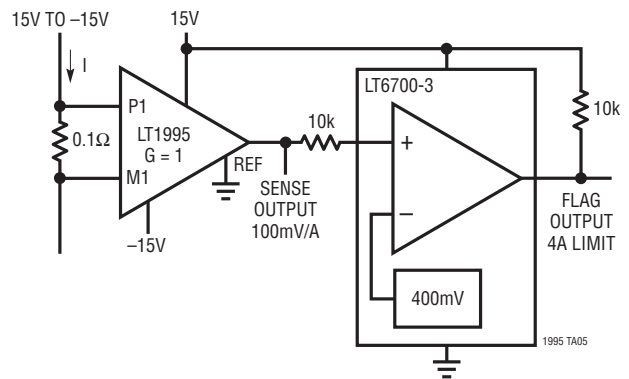
Figure 52. Fast Current Sense with Alarm

BIDIRECTIONAL

Bidirectional Current Sense with Separate Charge/Discharge Output (Figure 53)

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 LT6101, 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.

Bidirectional Absolute Value Current Sense (Figure 54)

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.


DISCHARGING: $V_{OUT\,D} = I_{DISCHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT\,D}}{R_{IN\,D}} \right)$ WHEN $I_{DISCHARGE} \geq 0$

CHARGING: $V_{OUT\,C} = I_{CHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT\,C}}{R_{IN\,C}} \right)$ WHEN $I_{CHARGE} \geq 0$
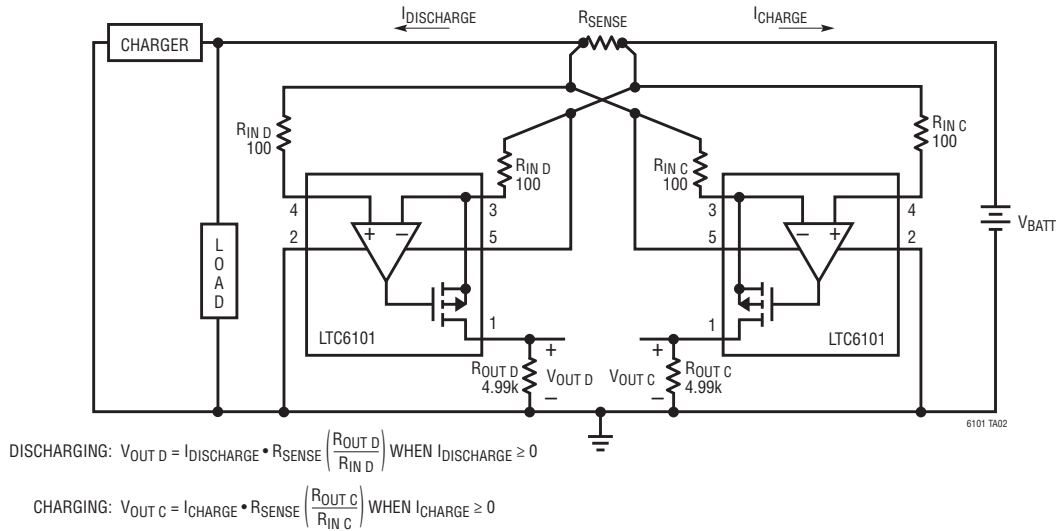
Figure 53. Bidirectional Current Sense with Separate Charge/Discharge Output

DISCHARGING: $V_{OUT} = I_{DISCHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT}}{R_{IN\,D}} \right)$ WHEN $I_{DISCHARGE} \geq 0$

CHARGING: $V_{OUT} = I_{CHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT}}{R_{IN\,C}} \right)$ WHEN $I_{CHARGE} \geq 0$
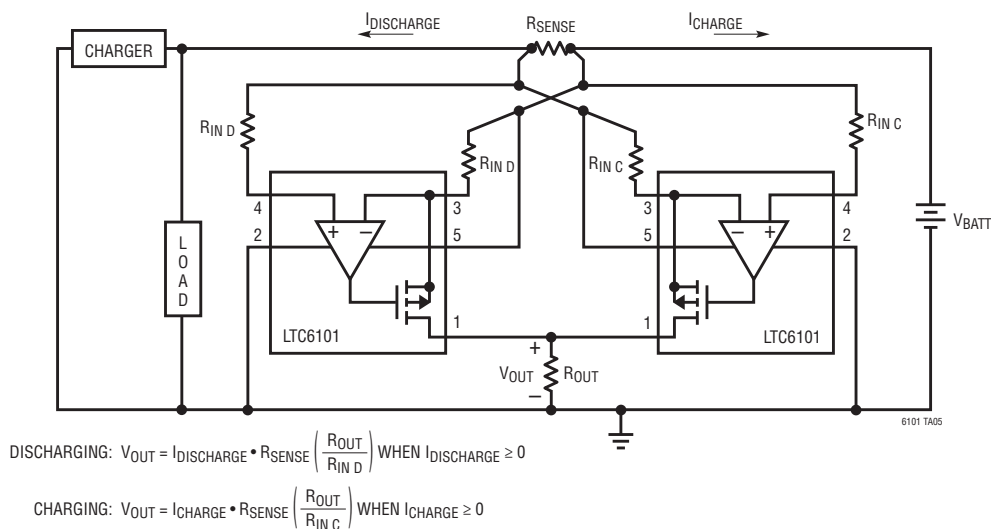
Figure 54. Bidirectional Absolute Value Current Sense

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BIDIRECTIONAL

Full-Bridge Load Current Monitor (Figure 55)

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.

Low Power, Bidirectional 60V Precision High Side Current Sense (Figure 56)

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.
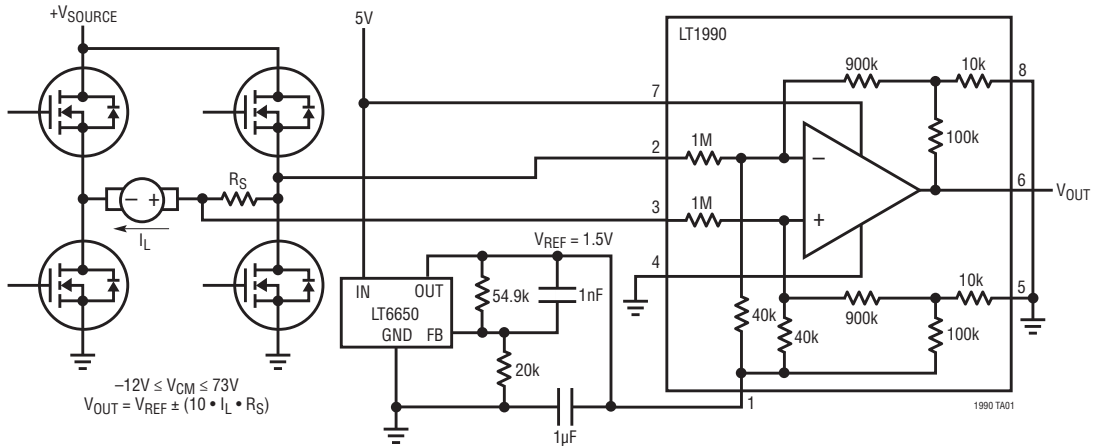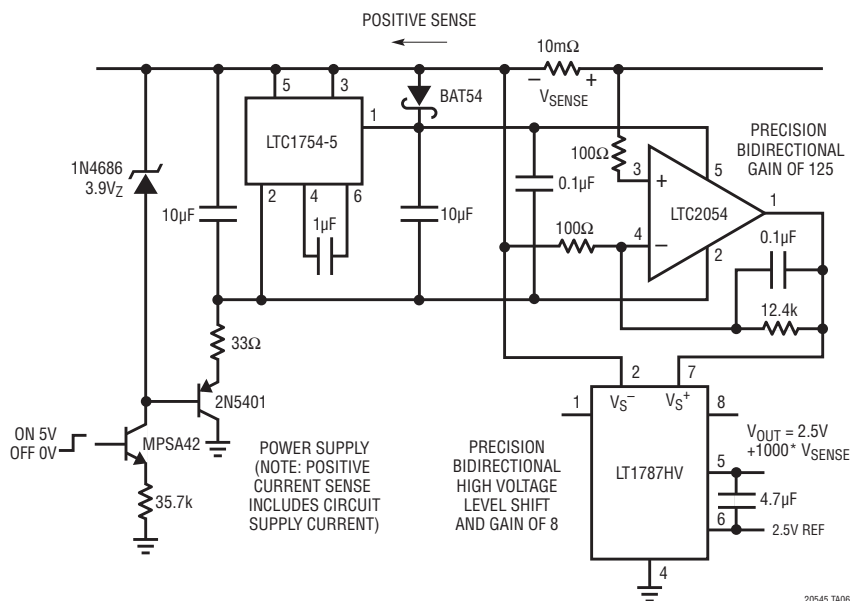

Figure 55. Full-Bridge Load Current Monitor

Figure 56. Low Power, Bidirectional 60V Precision High Side Current Sense

BIDIRECTIONAL

Split or Single Supply Operation, Bidirectional Output into A/D (Figure 57)

In this circuit, split supply operation is used on both the LT1787 and LT1404 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 midspan of the ADC input range.

Bidirectional Precision Current Sensing (Figure 58)

This circuit uses two LTC6102 devices, one for each direction of current flow through a single sense resistance. While each output only provides a result in one particular direction of current, taking the two output signals differentially provides a bipolar signal to other circuitry such as an ADC. Since each circuit has its own gain resistors, bilinear scaling is possible (different scaling depending on direction).
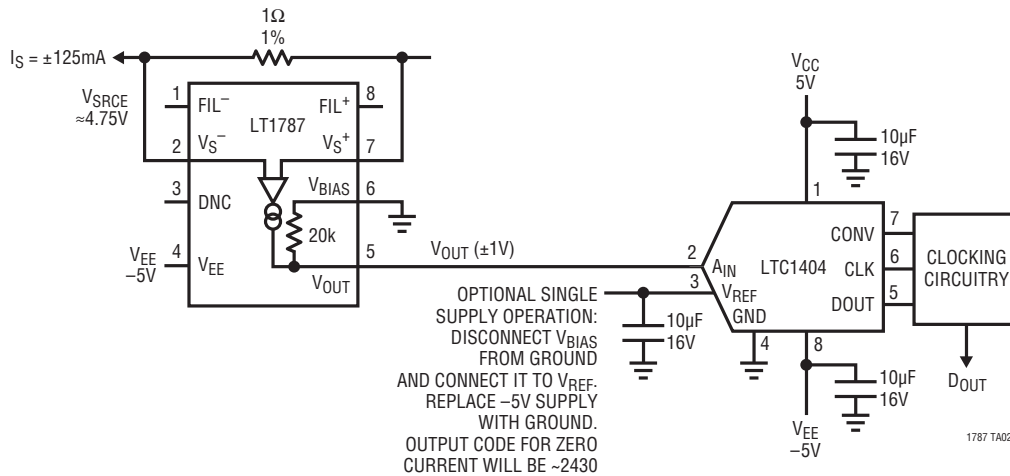
Figure 57. Split or Single Supply Operation, Bidirectional Output into A/D
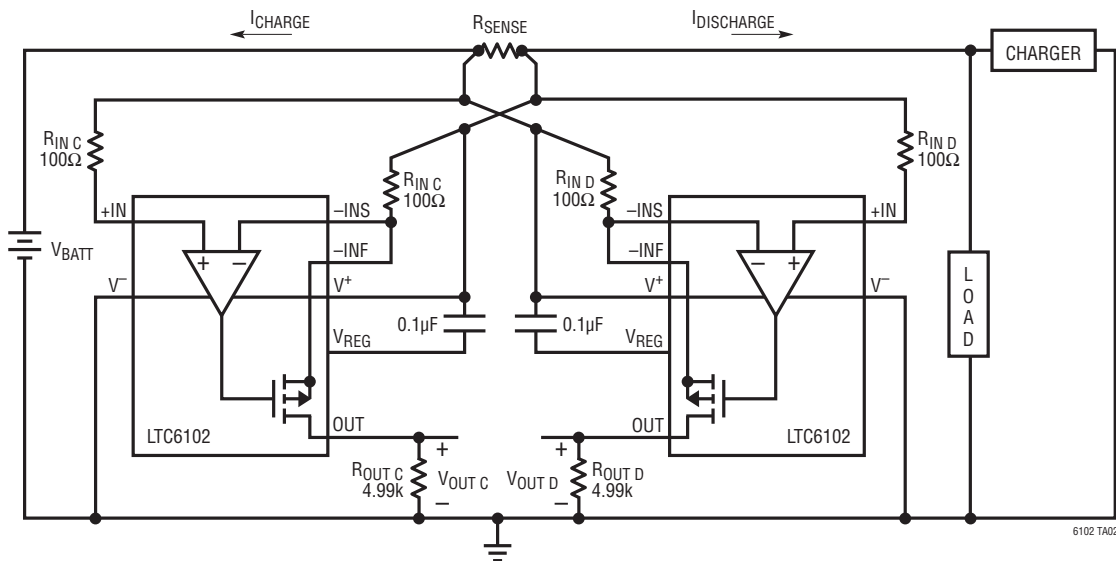
DISCHARGING: $V_{OUT\,D} = I_{DISCHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT\,D}}{R_{IN\,D}} \right)$ WHEN $I_{DISCHARGE} \geq 0$

CHARGING: $V_{OUT\,C} = I_{CHARGE} \bullet R_{SENSE} \left(\dfrac{R_{OUT\,C}}{R_{IN\,C}} \right)$ WHEN $I_{CHARGE} \geq 0$

Figure 58. Bidirectional Precision Current Sensing

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LINEAR
TECHNOLOGY

BIDIRECTIONAL

Differential Output Bidirectional 10A Current Sense (Figure 59)

The LTC6103 has dual sense amplifiers and each measures current in one direction through a single sense resistance. The outputs can be taken together as a differential output to subsequent circuitry such as an ADC. Values shown are for 10A maximum measurement.

Absolute Value Output Bidirectional Current Sensing (Figure 60)

Connecting an LTC6103 so that the outputs each represent opposite current flow through a shared sense resistance, but with the outputs driving a common load, results in a positive only output function while sensing bidirectionally.
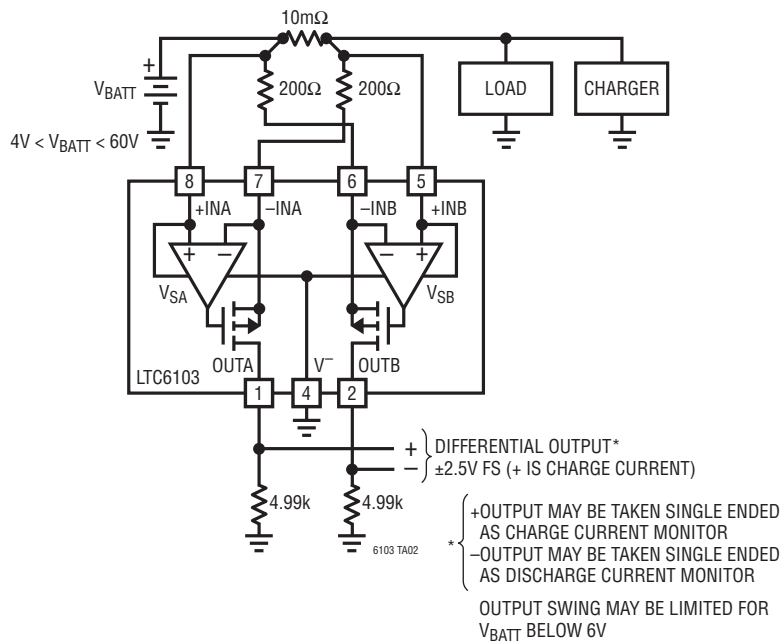
Figure 59. Differential Output Bidirectional 10A Current Sense
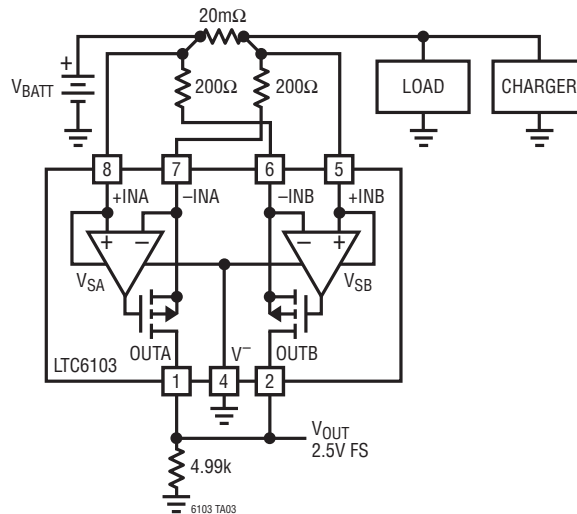
Figure 60. Absolute Value Output Bidirectional Current Sensing

BIDIRECTIONAL

More Bidirectional Circuits Are Shown in Other Chapters:

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.

Single-Supply RMS Current Measurement (Figure 61)

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 trans-former 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.
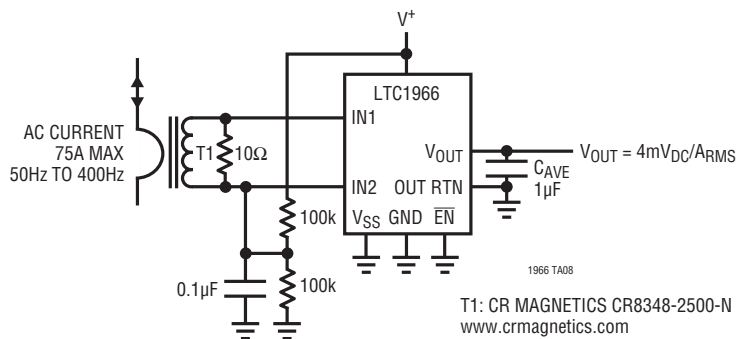
Figure 61. Single-Supply RMS Current Measurement

More AC Circuits Are Shown in Other Chapters:

FIGURE	TITLE
120	Bidirectional Current Sensing in H-Bridge Drivers
124	Monitor H-Bridge Motor Current Directly
128	Fixed Gain DC Motor Current Monitor

DC

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

Micro-Hotplate Voltage and Current Monitor (Figure 62)

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 (Figure 63)

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.

$$V_O = I_L \left(\frac{R_B}{R_A}\right) R_{SENSE}$$

FOR $R_A = 1k$, $R_B = 10k$

$$\frac{V_O}{I_L} = 1V/A$$

Figure 63. Battery Current Monitor

Current Monitor: $V_{OUT} = 500mV/mA$

Voltage Monitor: $V_{OUT} = \dfrac{V_{DR}^+ - V_{DR}^-}{10}$

www.bostonmicrosystems.com
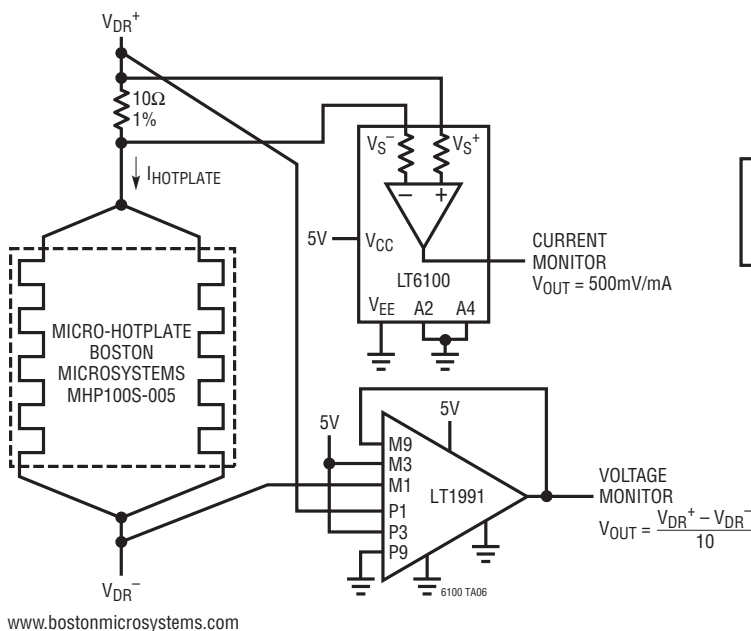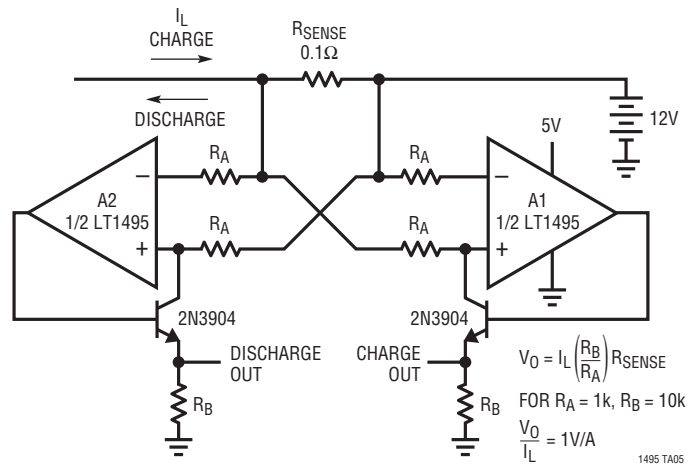
Figure 62. Micro-Hotplate Voltage and Current Monitor

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DC

Bidirectional Battery-Current Monitor (Figure 64)

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.
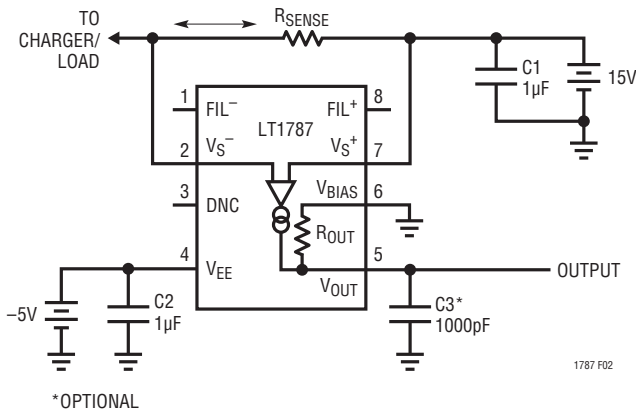
*OPTIONAL

Figure 64. Bidirectional Battery-Current Monitor

"Classic" Positive Supply Rail Current Sense (Figure 65)

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 (Figure 66)

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 1µA max from the battery bus.
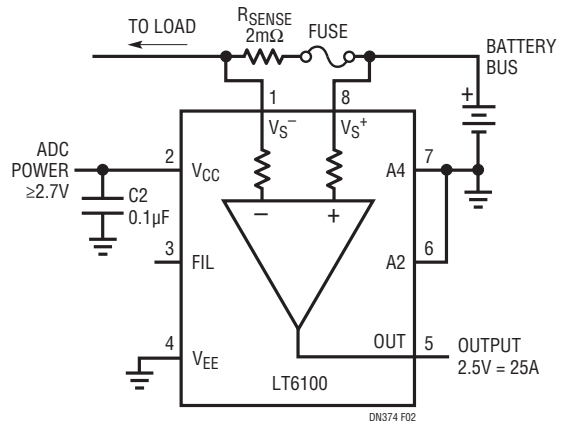
Figure 66. High Side Current Sense and Fuse Monitor

Figure 65. "Classic" Positive Supply Rail Current Sense

DC

Gain of 50 Current Sense (Figure 67)

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.
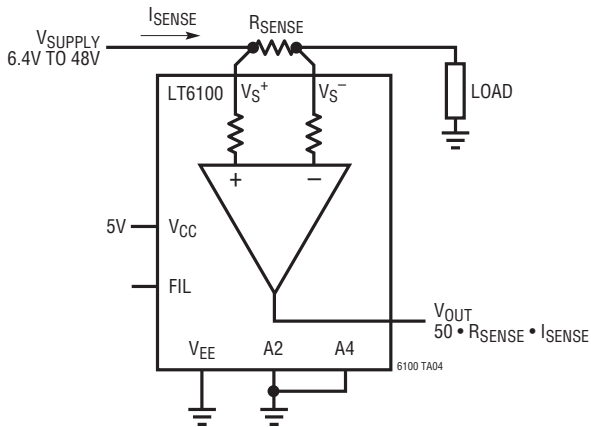
Figure 67. Gain of 50 Current Sense

Dual LTC6101's Allow High-Low Current Ranging (Figure 68)

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 currents, less than 1.2A, than with higher currents. A comparator detects higher current flow, up to 10A, and switches sensing over to the high current circuitry.
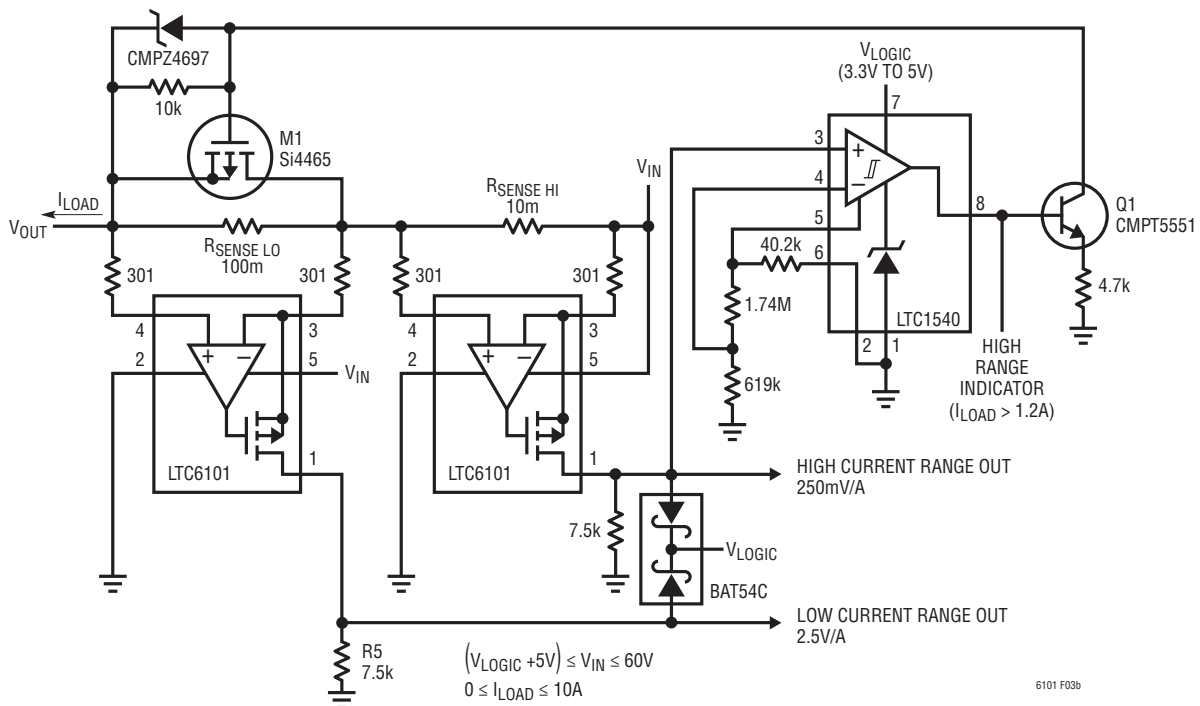
Figure 68. Dual LTC6101's Allow High-Low Current Ranging

DC

Two Terminal Current Regulator (Figure 69)

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.

$$I_{OUT} = \frac{(R2 + R3)V_{REF}}{(R1)(R3)}$$
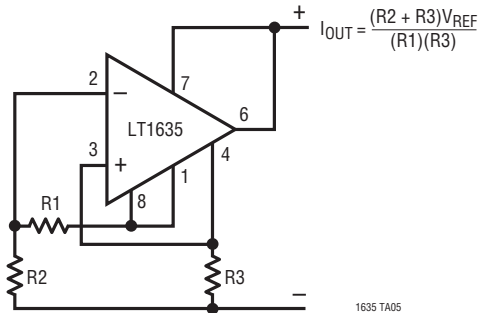
Figure 69. Two Terminal Current Regulator

High Side Power Supply Current Sense (Figure 70)

The low offset error of the LTC6800 allows for unusually low sense resistance while retaining accuracy.
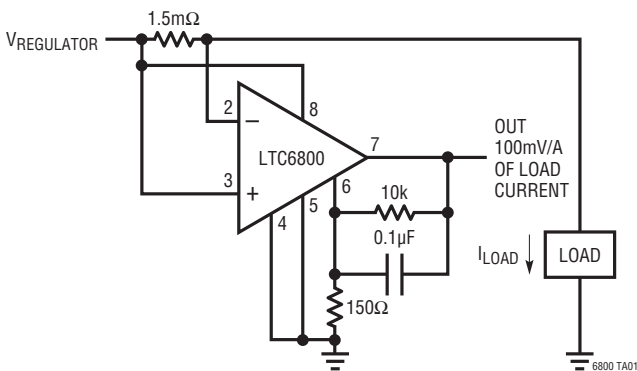
Figure 70. High Side Power Supply Current Sense

0nA to 200nA Current Meter (Figure 71)

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 micropower op amp so the quiescent current drain from the batteries is very low and thus no on/off switch is required.
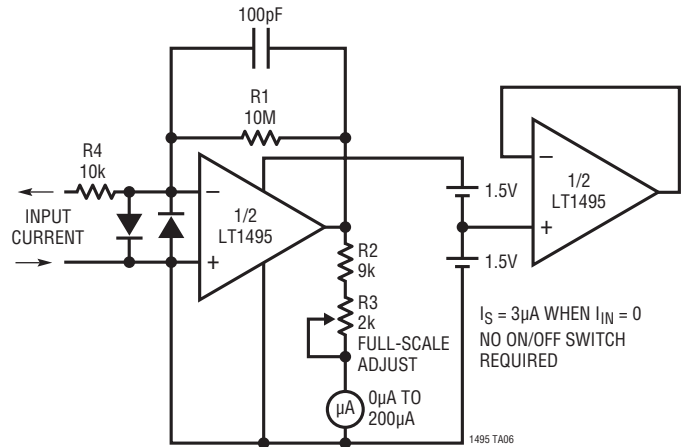
Figure 71. 0nA to 200nA Current Meter

Over-The-Top Current Sense (Figure 72)

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.
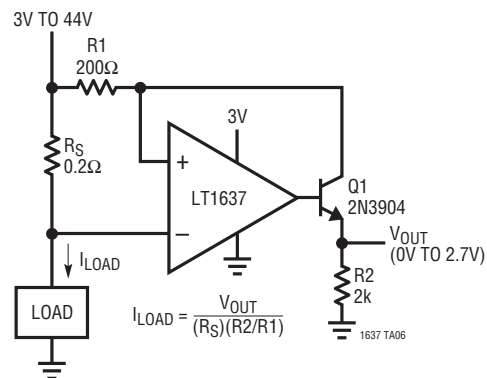
Figure 72. Over-The-Top Current Sense

DC

Conventional H-Bridge Current Monitor (Figure 73)

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 (Figure 74)

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.
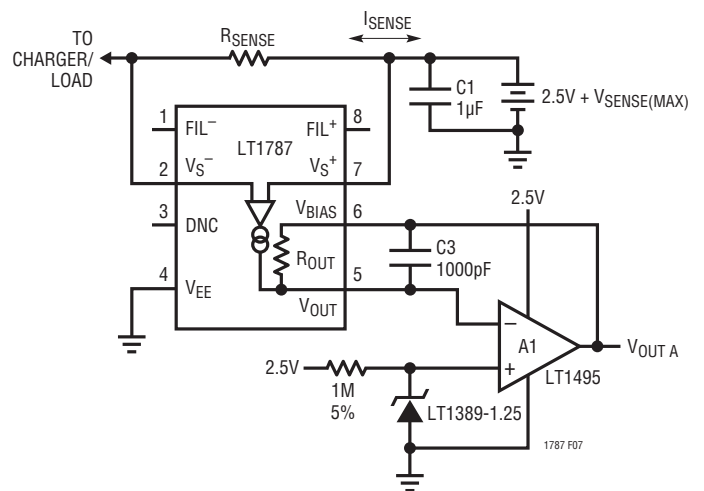
Figure 74. Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter

Figure 73. Conventional H-Bridge Current Monitor

DC

Battery Current Monitor (Figure 75)

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 (Figure 76)

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/µs 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 (Figure 77)

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 R2 (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.

$$V_O = I_L \left(\frac{R_B}{R_A}\right) R_{SENSE}$$

FOR R_A = 1k, R_B = 10k

$$\frac{V_O}{I_L} = 1V/A$$
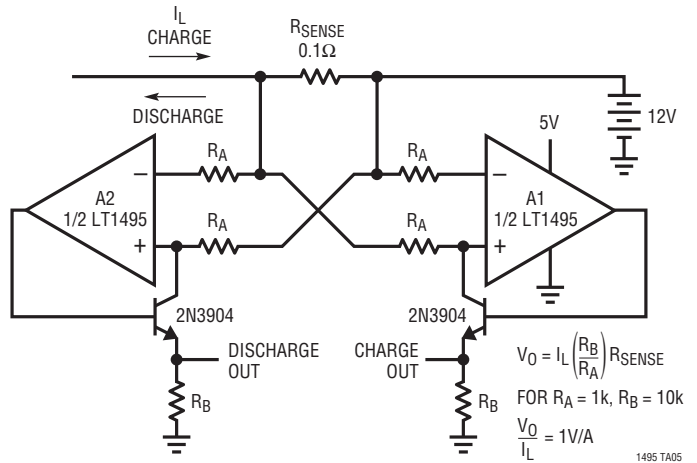
Figure 75. Battery Current Monitor
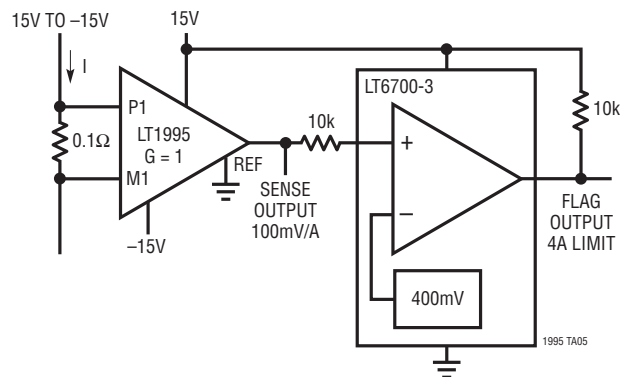
Figure 76. Fast Current Sense with Alarm

$$V_O = I_{LOAD} \cdot R_S \left(\frac{R2}{R1}\right)$$

$$= I_{LOAD} \cdot 20\Omega$$
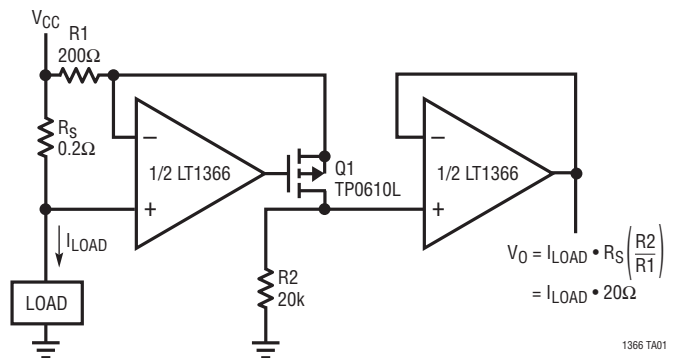
Figure 77. Positive Supply Rail Current Sense

DC

LT6100 Load Current Monitor (Figure 78)

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 (Figure 79)

This is a simple controlled current sink, where the op amp drives the N-MOSFET 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 (Figure 80)

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.

Figure 78. LT6100 Load Current Monitor

Figure 79. 1A Voltage-Controlled Current Sink
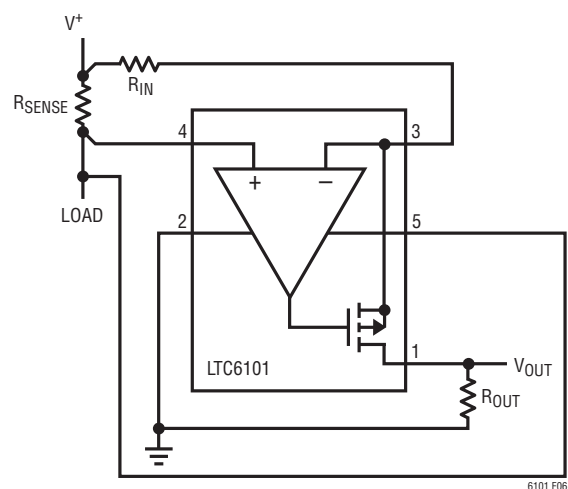
Figure 80. LTC6101 Supply Current Included as Load in Measurement

an105fa

DC

V+ Powered Separately from Load Supply (Figure 81)

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.

Simple High Side Current Sense Using the LTC6101 (Figure 82)

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 1µs 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 250µA supply current when the load is off.

"Classic" High Precision Low Side Current Sense (Figure 83)

This configuration is basically a standard noninverting 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.
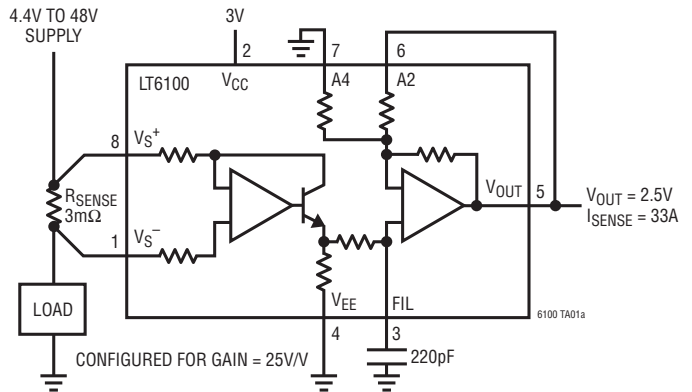
Figure 81. V+ Powered Separately from Load Supply
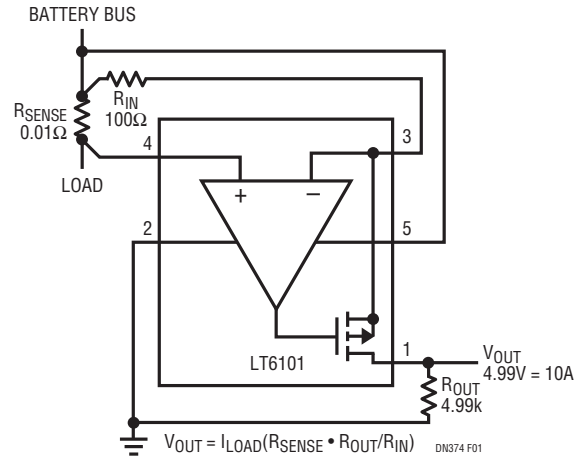
Figure 82. Simple High Side Current Sense Using the LTC6101
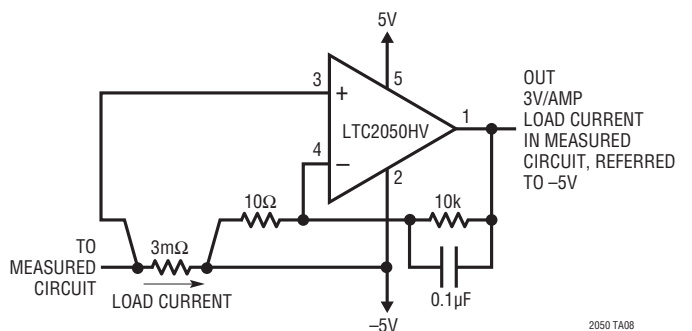
Figure 83. "Classic" High Precision Low Side Current Sense

an105fa

DC

More DC Circuits Are Shown in Other Chapters:

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.

Over-The-Top Current Sense (Figure 84)

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.
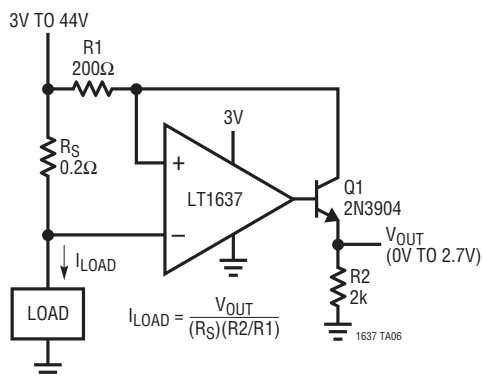
Figure 84. Over-The-Top Current Sense

V+ Powered Separately from Load Supply (Figure 85)

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 (Figure 86)

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}.
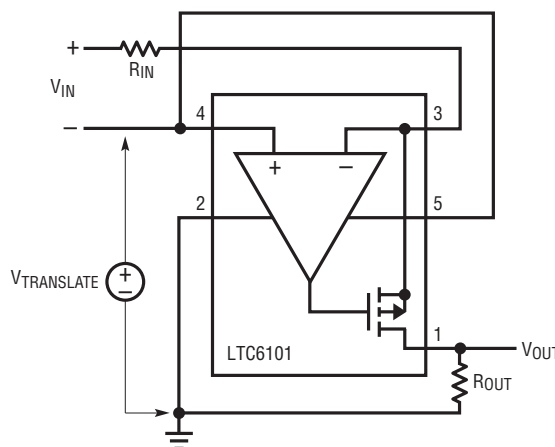
Figure 86. Voltage Translator
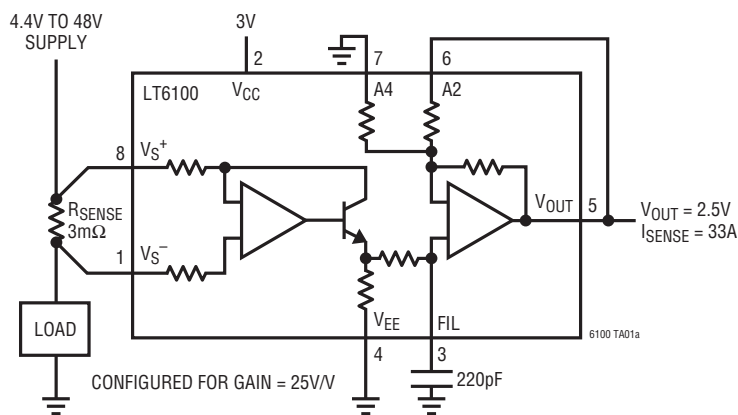
Figure 85. V+ Powered Separately from Load Supply

LEVEL SHIFTING

Low Power, Bidirectional 60V Precision High Side Current Sense (Figure 87)

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.

Figure 87. Low Power, Bidirectional 60V Precision High Side Current Sense

More Level Shifting Circuits Are Shown in Other Chapters:

FIGURE	TITLE
40	Monitor Current in Positive or Negative Supply Lines

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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.

Over-The-Top Current Sense (Figure 88)

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 (Figures 89a and 89b)

The upper circuit (a) uses an instrumentation amplifier (IA) powered by a separate rail (>1V above V_{IN}) to measure across the 1kΩ current shunt. The lower figure (b) 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.
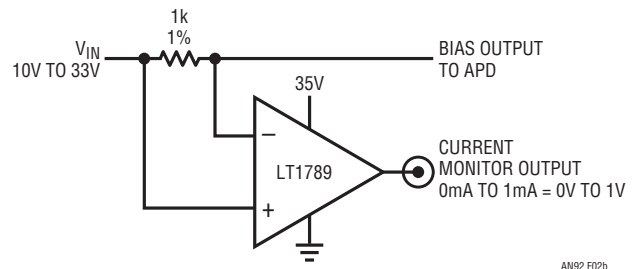
Figure 89a
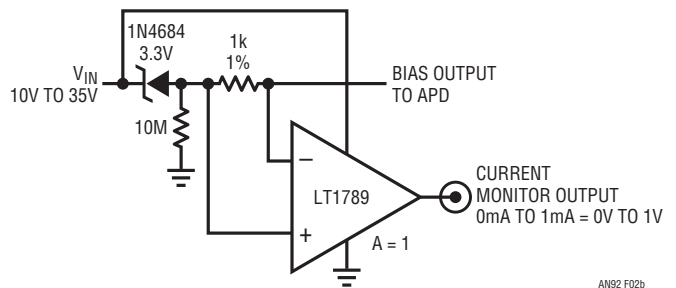
Figure 89b

Figure 89. Measuring Bias Current Into an Avalanche Photo Diode (APD) Using an Instrumentation Amplifier

$$I_{LOAD} = \frac{V_{OUT}}{(R_S)(R2/R1)}$$

Figure 88. Over-The-Top Current Sense

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HIGH VOLTAGE

Simple 500V Current Monitor (Figure 90)

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 (Figure 91)

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.

DANGER! Lethal Potentials Present — Use Caution

DANGER!! HIGH VOLTAGE!!

M1 AND M2 ARE FQD3P50 TM

$$V_{OUT} = \frac{R_{OUT}}{R_{IN}} \cdot V_{SENSE} = 49.9 \ V_{SENSE}$$

6101 TA09
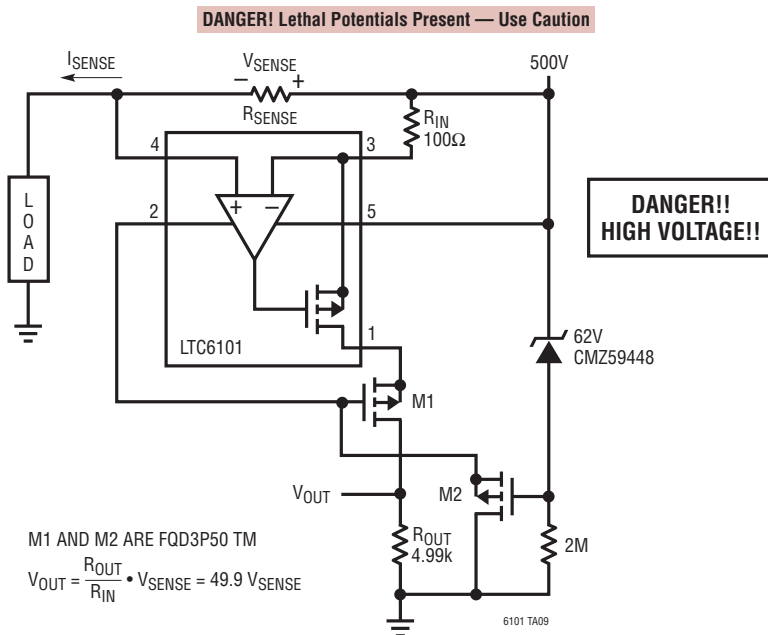
Figure 90. Simple 500V Current Monitor

N = OPTO-ISOLATOR CURRENT GAIN

$$V_{OUT} = V_{LOGIC} - I_{SENSE} \cdot \frac{R_{SENSE}}{R_{IN}} \cdot N \cdot R_{OUT}$$

6101 TA08
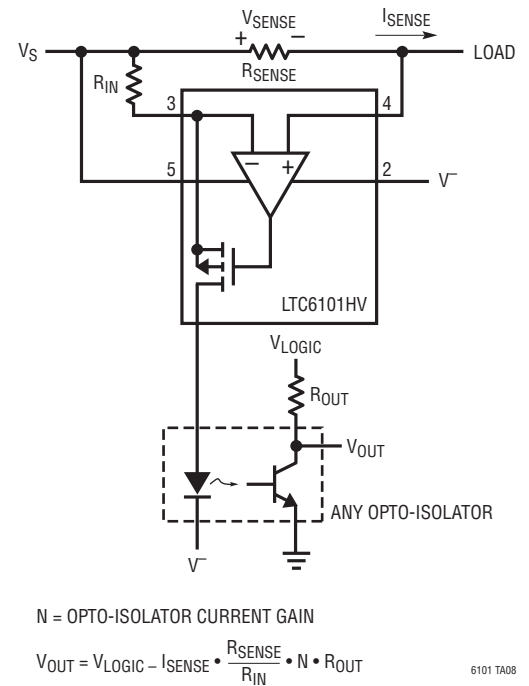
Figure 91. 48V Supply Current Monitor with Isolated Output and 105V Survivability

an105fa

HIGH VOLTAGE

Low Power, Bidirectional 60V Precision High Side Current Sense (Figure 92)

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.
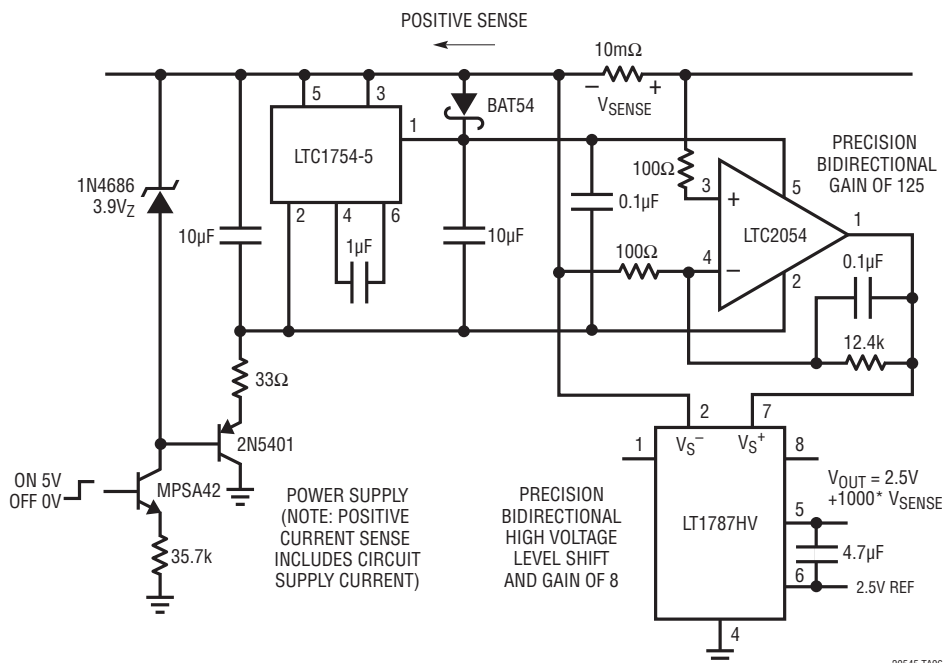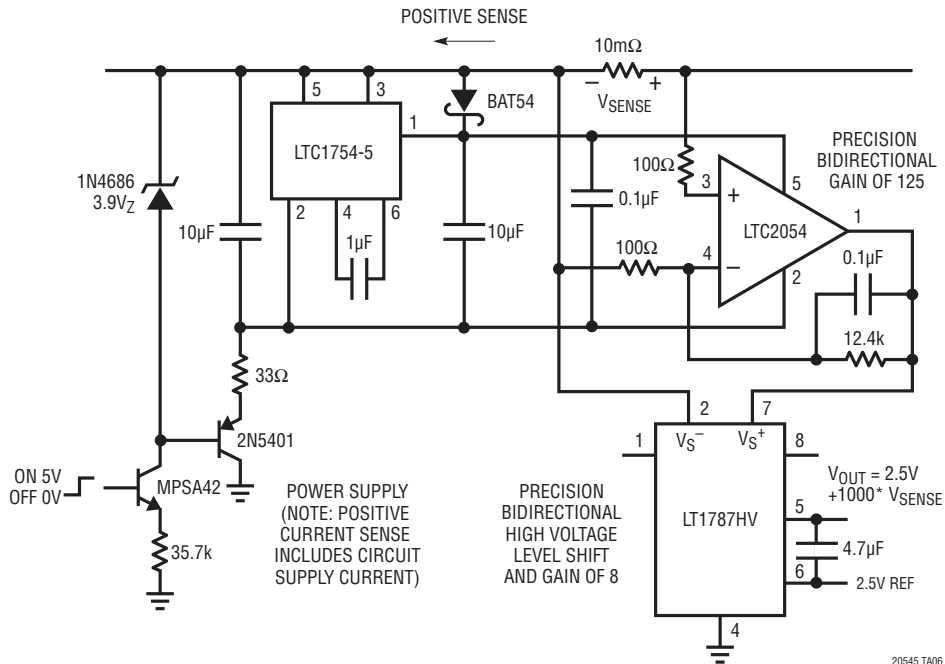

Figure 92. Low Power, Bidirectional 60V Precision High Side Current Sense

HIGH VOLTAGE

High Voltage Current and Temperature Monitoring (Figure 93)

Combining an LTC2990 ADC converter with a high voltage LTC6102HV current sense amplifier allows the measurement of very high voltage rails, up to 104V, and very high current loads. The current sense amplifier outputs a ground referenced voltage proportional to the load current and is measured as a single ended input by the ADC. A divided down representation of the supply voltage is a second input. An external NPN transistor serves as a remote temperature sensor.

VOLTAGE, CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V_{LOAD}	REG 6, 7	13.2mVLSB
V2(I_{LOAD})	REG 8, 9	1.223mA/LSB
T_{REMOTE}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18μV/LSB

Figure 93. High Voltage Current and Temperature Monitoring

HIGH VOLTAGE

More High Voltage Circuits Are Shown In Other Chapters:

LOW VOLTAGE

Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter (Figure 94)

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 noninverting 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.
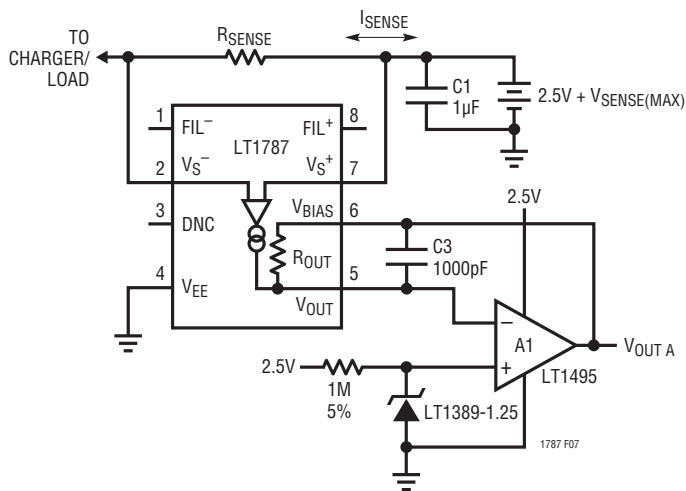
Figure 94. Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter

1.25V Electronic Circuit Breaker (Figure 95)

The LTC4213 provides protection and automatic circuit breaker action by sensing drain-to-source voltage drop across the N-MOSFET. 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.
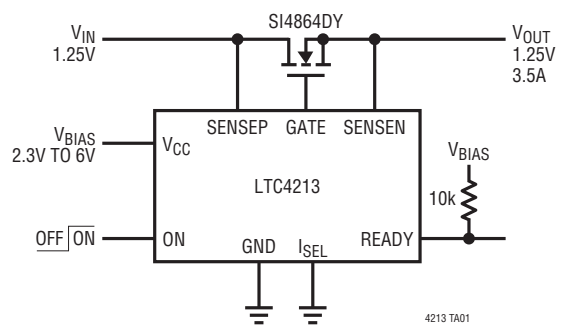
Figure 95. 1.25V Electronic Circuit Breaker

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

Kelvin Input Connection Preserves Accuracy Despite Large Load Currents (Figure 96)

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.
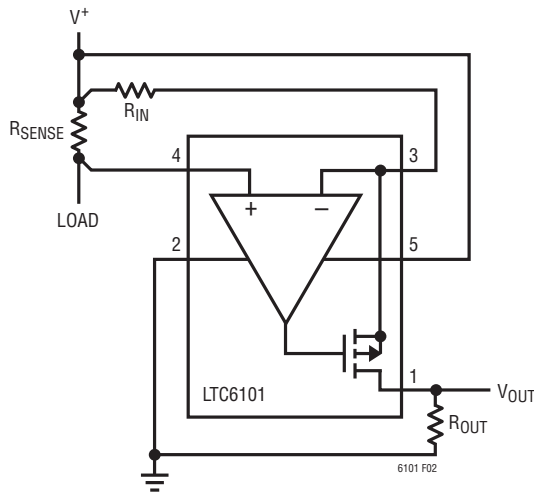
Figure 96. Kelvin Input Connection Preserves Accuracy Despite Large Load Currents

Shunt Diode Limits Maximum Input Voltage to Allow Better Low Input Resolution Without Over-Ranging the LTC6101 (Figure 97)

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.
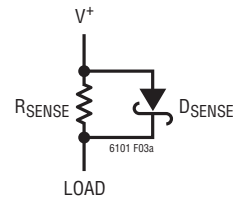
Figure 97. Shunt Diode Limits Maximum Input Voltage to Allow Better Low Input Resolution Without Over-Ranging the LTC6101

Kelvin Sensing (Figure 98)

In any high current, >1A, 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 IxR voltage drop errors are developed.
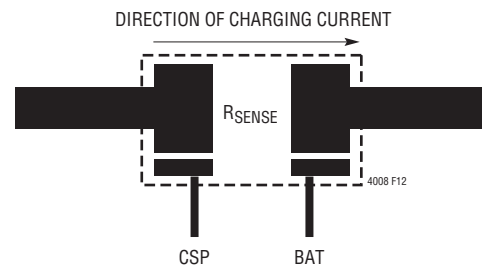
Figure 98. Kelvin Sensing

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HIGH CURRENT (100mA to Amps)

0A to 33A High Side Current Monitor with Filtering (Figure 99)

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 lowpass corner frequency).

Single Supply RMS Current Measurement (Figure 100)

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.
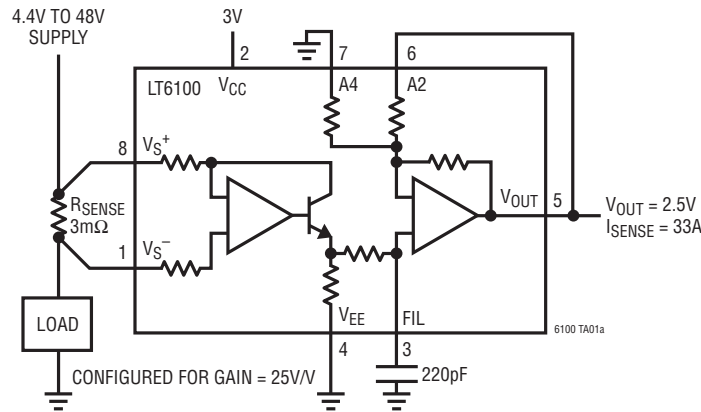
Figure 99. 0A to 33A High Side Current Monitor with Filtering
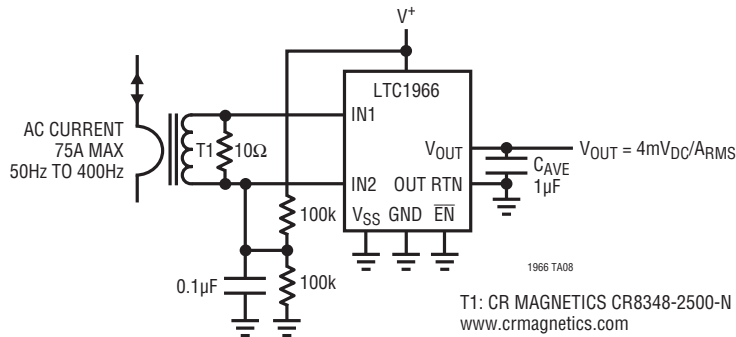
Figure 100. Single Supply RMS Current Measurement

HIGH CURRENT (100mA to Amps)

Dual LTC6101's Allow High-Low Current Ranging (Figure 101)

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 currents, less than 1.2A, than with higher currents. A comparator detects higher current flow, up to 10A, and switches sensing over to the high current circuitry.
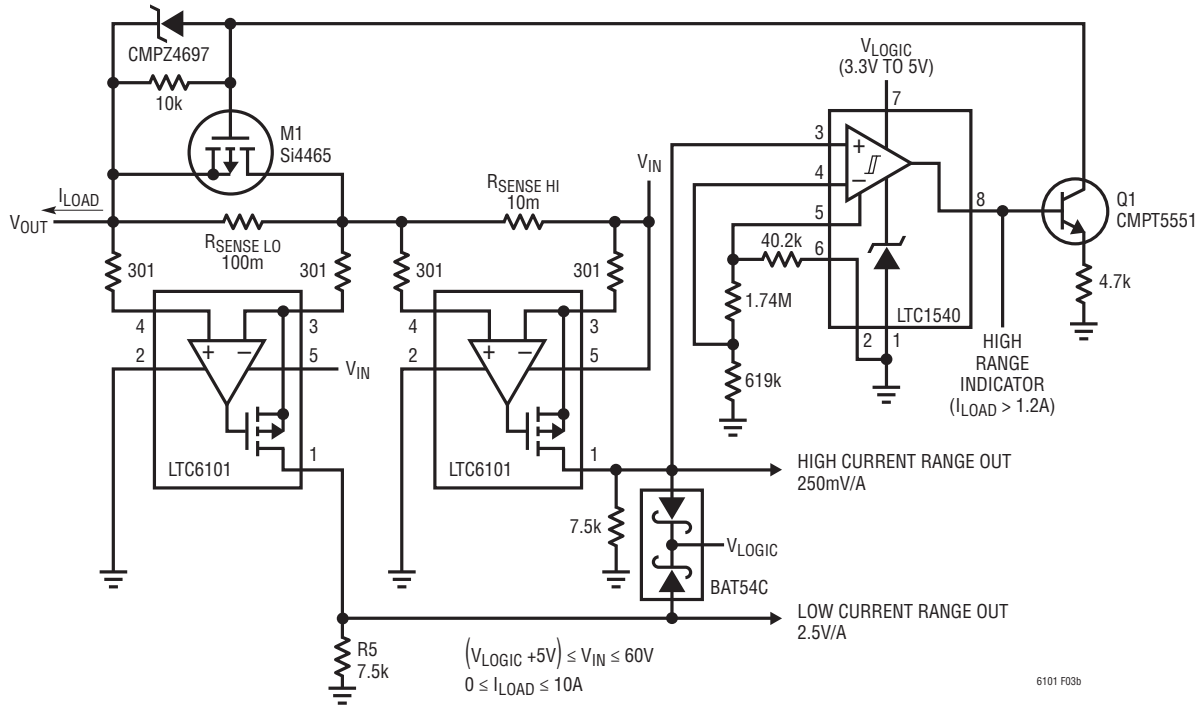
Figure 101. Dual LTC6101's Allow High-Low Current Ranging

HIGH CURRENT (100mA to Amps)

LDO Load Balancing (Figure 102)

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'ed to match the master regulator output voltage. The precise low offset voltage of the LTC6078 dual op amp (10μV) 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.
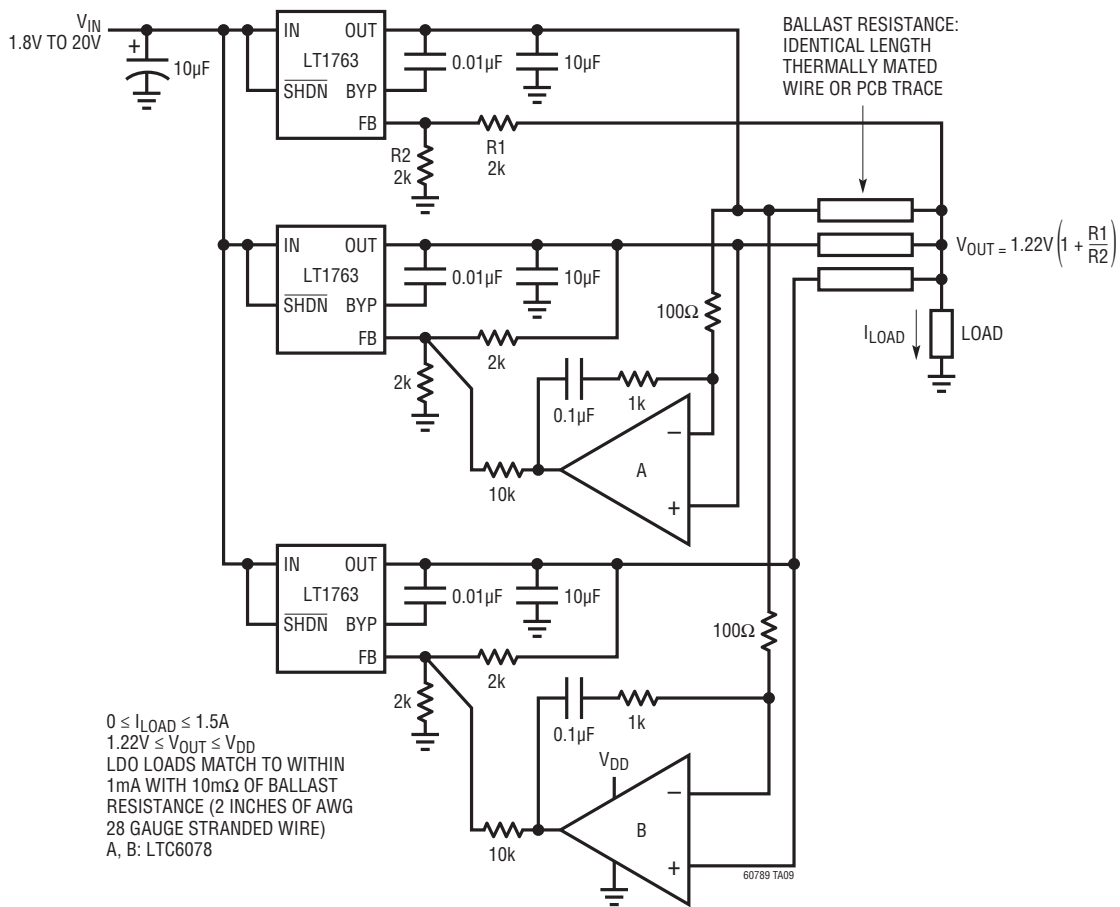
Figure 102. LDO Load Balancing

HIGH CURRENT (100mA to Amps)

Sensing Output Current (Figure 103)

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.
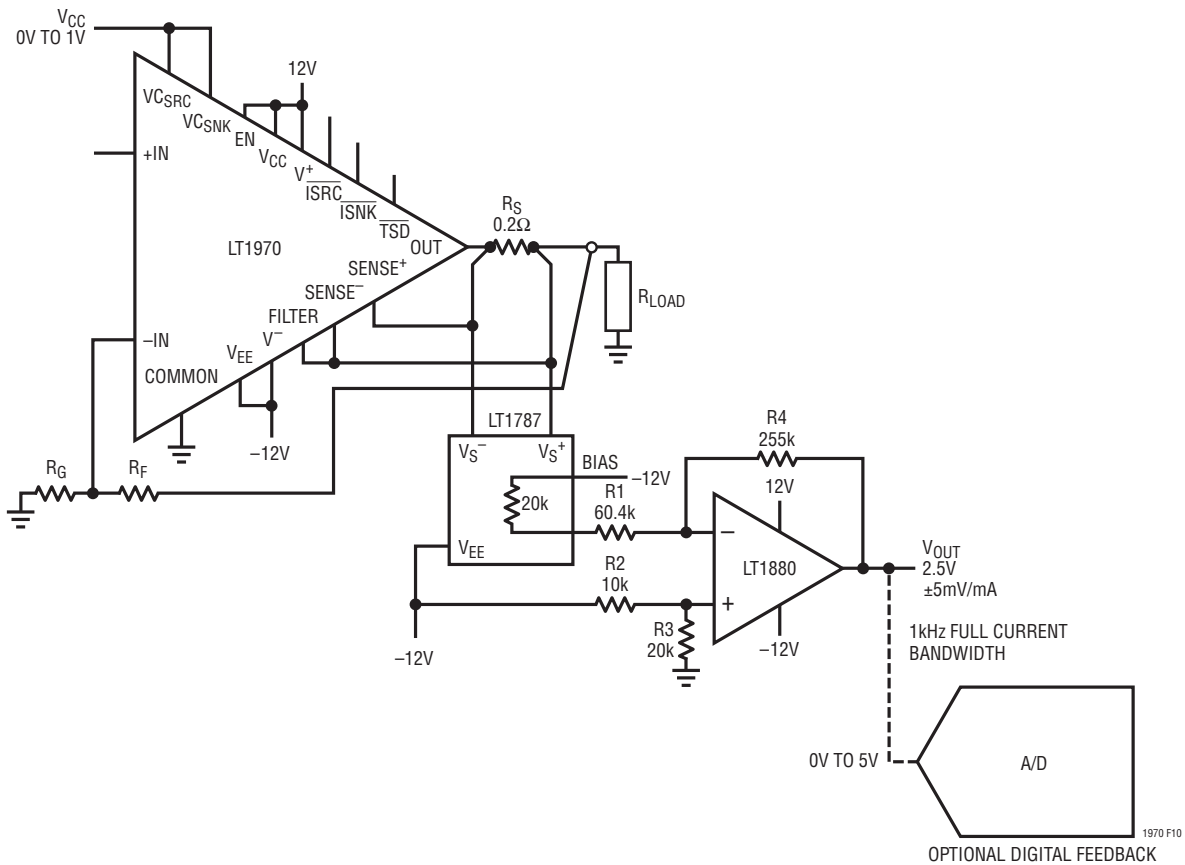
Figure 103. Sensing Output Current

HIGH CURRENT (100mA to Amps)

Using Printed Circuit Sense Resistance (Figure 104)

The outstanding LTC6102 precision allows the use of sense resistances fabricated with conventional printed circuit techniques. For "one ounce" copperclad, the trace resistance is approximately (L/W)·0.0005Ω and can carry about 4A per mm of trace width. The example below shows a practical 5A monitoring solution with both L and W set to 2.5mm. The resistance is subject to about +0.4%/°C temperature change and the geometric tolerances of the fabrication process, so this will not generally be for high accuracy work, but can be useful in various low cost protection and status monitoring functions.
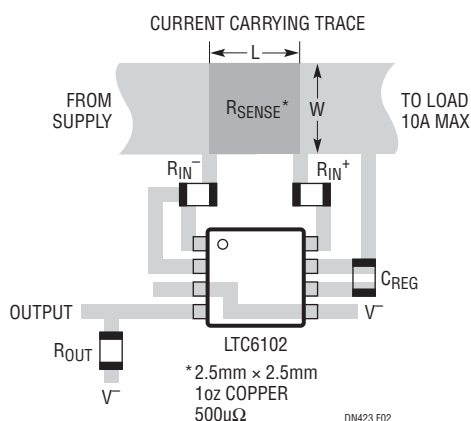
Figure 104. Using Printed Circuit Sense Resistance

High Voltage, 5A High Side Current Sensing in Small Package (Figure 105)

The LT6106 is packaged in a small SOT-23 package but still operates over a wide supply range of 3V to 44V. Just two resistors set the gain (10 in circuit shown) and the output is a voltage referred to ground.
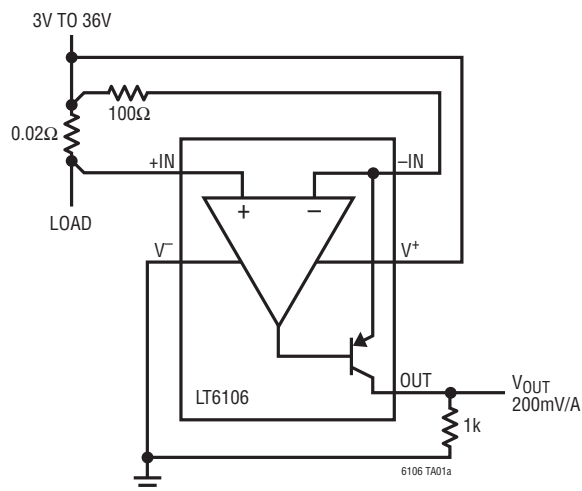
Figure 105. High Voltage, 5A High Side Current Sensing in Small Package

More High Current Circuits Are Shown in Other Chapters:

FIGURE	TITLE
59	Differential Output Bidirectional 10A Current Sense
93	High Voltage Current and Temperature Monitoring
121	Single Output Provides 10A H-Bridge Current and Direction
179	Digitizing Charging and Loading Current in a Battery Monitor
209	Use Kelvin Connections to Maintain High Current Accuracy
215	0 to 10A Sensing Over Two Ranges

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 approach. Low current implies high source impedance measurements which are subject to noise pickup and often require filtering of some sort.

Filtered Gain of 20 Current Sense (Figure 106)

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 lowpass filter in the signal path. A capacitor of 1000pF as shown sets a filter corner frequency of 2.6KHz.
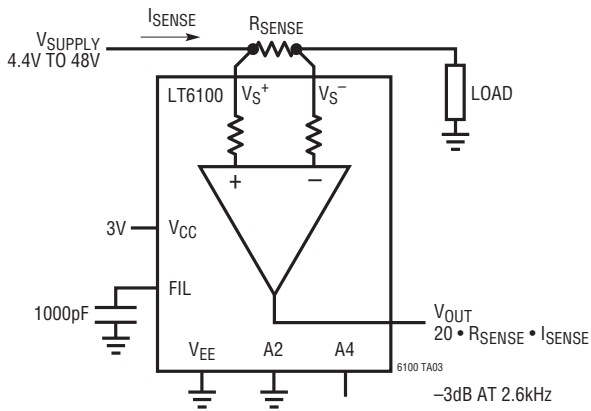
Figure 106. Filtered Gain of 20 Current Sense

Gain of 50 Current Sense (Figure 107)

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.
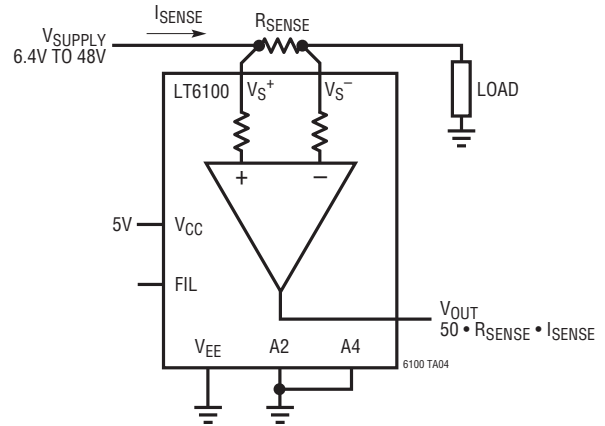
Figure 107. Gain of 50 Current Sense

0nA to 200nA Current Meter (Figure 108)

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 micropower op amp so the quiescent current drain from the batteries is very low and thus no on/off switch is required.
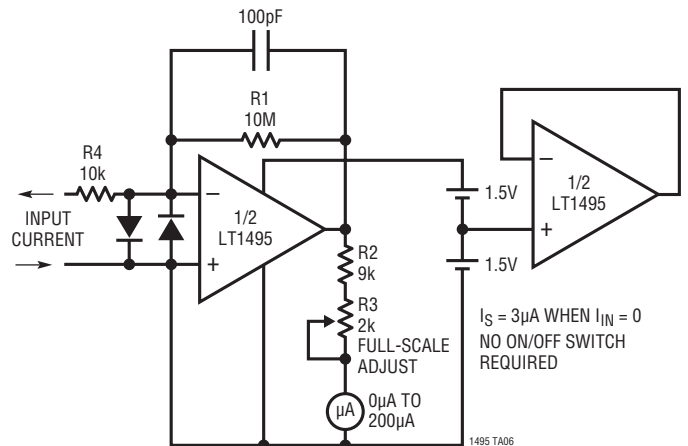
Figure 108. 0nA to 200nA Current Meter

LOW CURRENT
(Picoamps to Milliamps)

Lock-In Amplifier Technique Permits 1% Accurate APD Current Measurement Over 100nA to 1mA Range (Figure 109)

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 0.2µF 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 0.2µF 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 1kΩ shunt resistor's voltage drop. Verifying accuracy involves loading the APD bias line with 100nA to 1mA and noting output agreement.
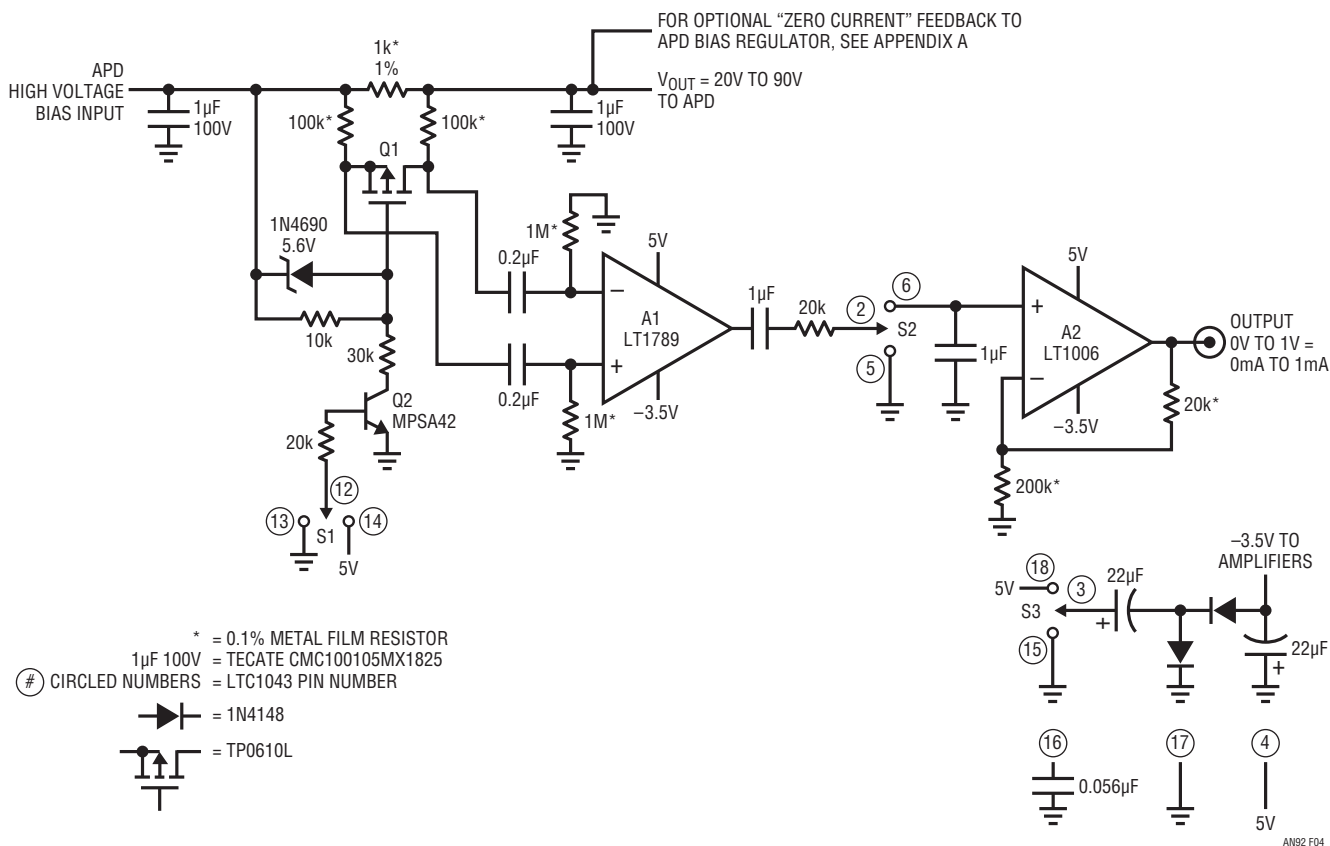
Figure 109. Lock-In Amplifier Technique Permits 1% Accurate APD Current Measurement Over 100nA to 1mA Range

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LOW CURRENT
(Picoamps to Milliamps)

DC-Coupled APD Current Monitor (Figure 110)

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.
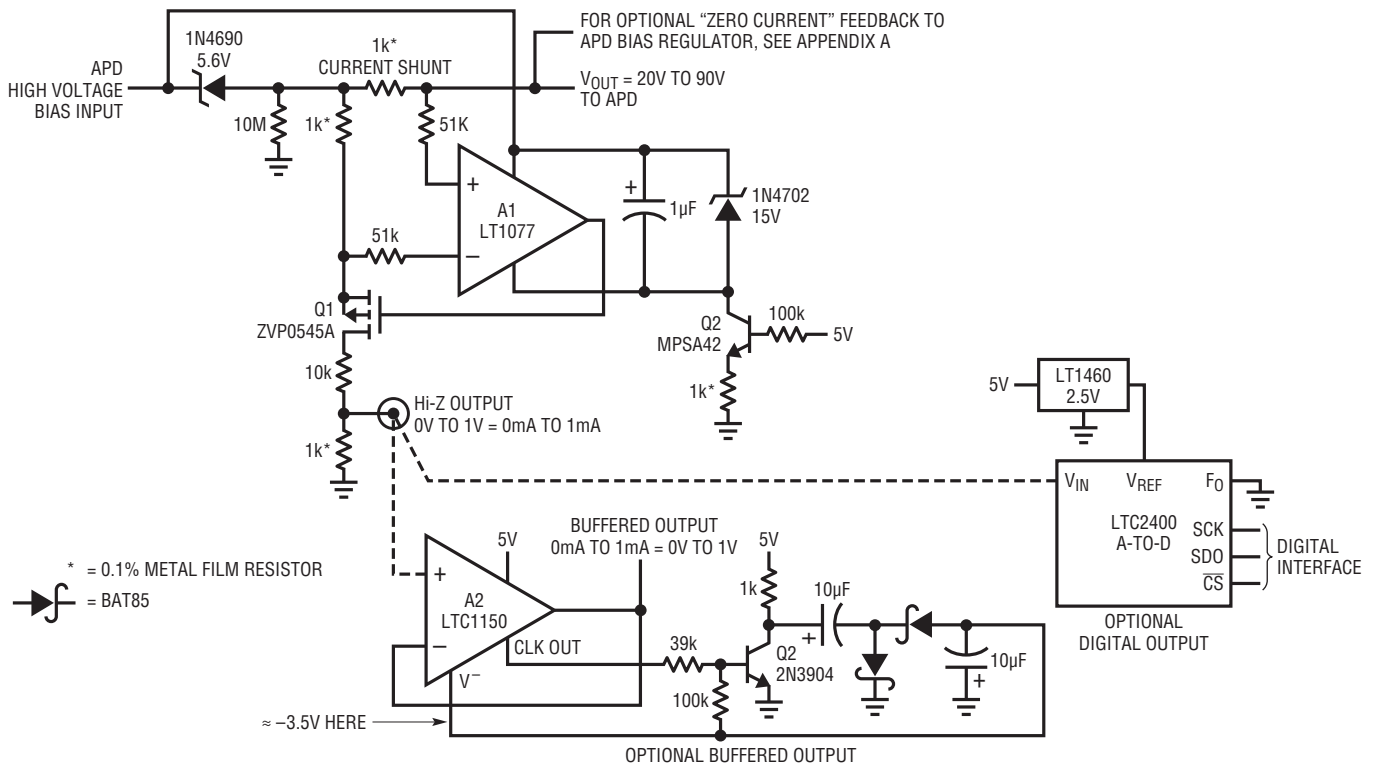
Figure 110. DC-Coupled APD Current Monitor

LOW CURRENT
(Picoamps to Milliamps)

Six Decade (10nA to 10mA) Current Log Amplifier (Figure 111)

Using precision quad amplifiers like the LTC6079, (10µV offset and <1pA 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.

10nA ≤ I_{IN} ≤ 10mA
Q1, Q2: DIODES INC. DMMT3906W
A TO D: LTC6079
$V_{OUT} \approx 150mV \cdot \log(I_{IN}) + 1.23V$, I_{IN} IN AMPS
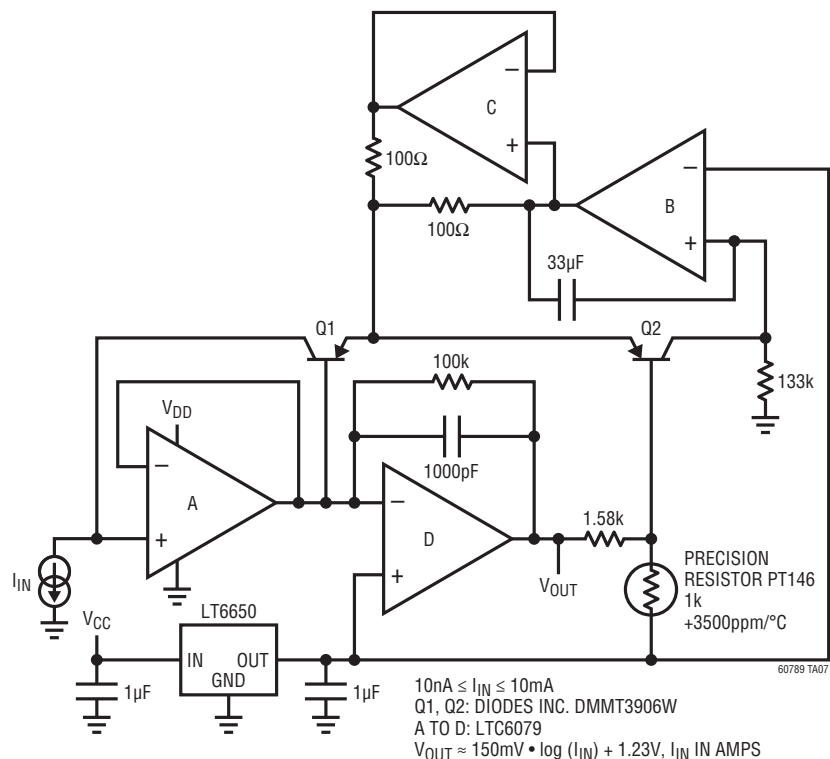
Figure 111. Six Decade (10nA to 10mA) Current Log Amplifier

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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.

Electronic Circuit Breaker (Figure 112)

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 RD and CD delay the action for 1ms. 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 reconnect the load after 200ms using the 0.22µF timer capacitor shown.

ALL COMPONENTS SHOWN ARE SURFACE MOUNT.
 * IMS026 INTERNATIONAL MANUFACTURING SERVICE, INC. (401) 683-9700
 ** RL2006-100-70-30-PT1 KEYSTONE CARBON COMPANY (814) 781-1591

LTC1153 • TA01

Figure 112. Electronic Circuit Breaker

Conventional H-Bridge Current Monitor (Figure 113)

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.

Figure 113. Conventional H-Bridge Current Monitor

Motor Speed Control (Figure 114)

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.

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MOTORS AND INDUCTIVE LOADS
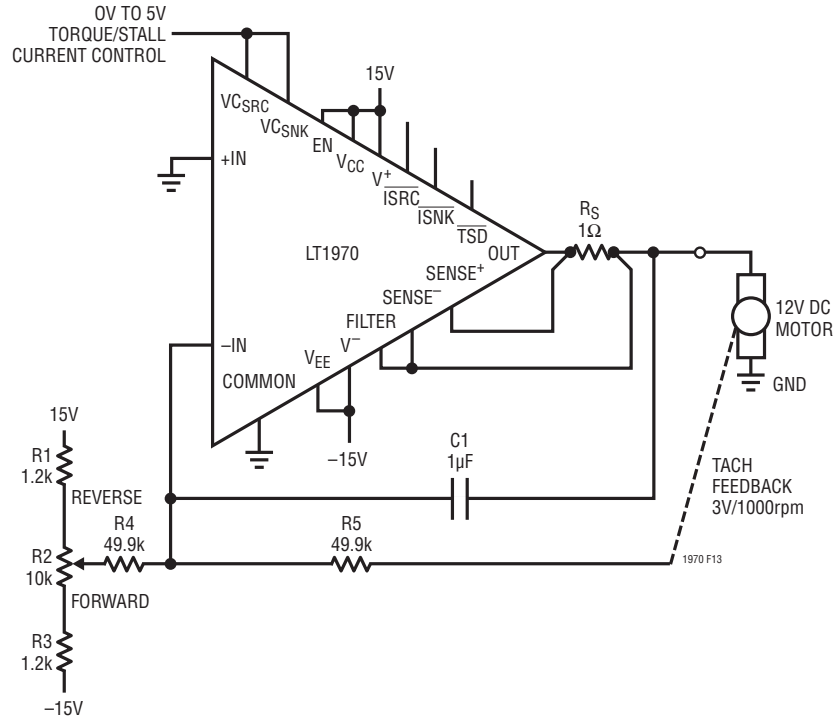
Figure 114. Motor Speed Control

Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information (Figure 115)

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 ΔΣADCs. The ΔΣADC 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.

Figure 115. Practical H-Bridge Current Monitor Offers Fault Detection and Bidirectional Load Information

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LINEAR
TECHNOLOGY

MOTORS AND INDUCTIVE LOADS

Lamp Driver (Figure 116)

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 (Figure 117)

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.

Figure 116. Lamp Driver

$$V_O = 49.9 \cdot R_S \cdot I_L$$

FOR $R_S = 5m\Omega$,
$V_O = 2.5V$ AT $I_L = 10A$ (FULL-SCALE)
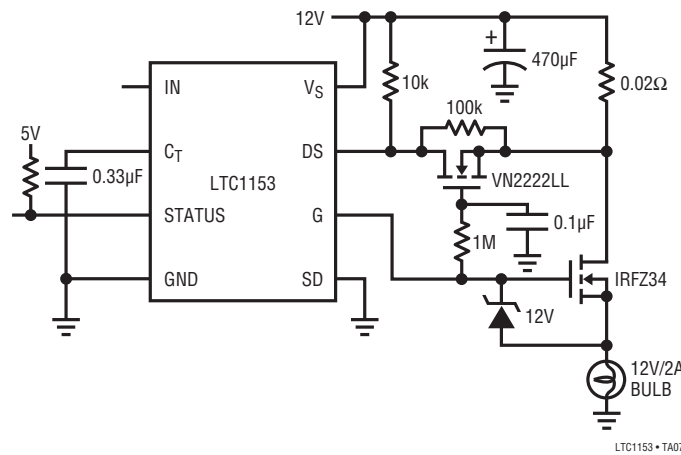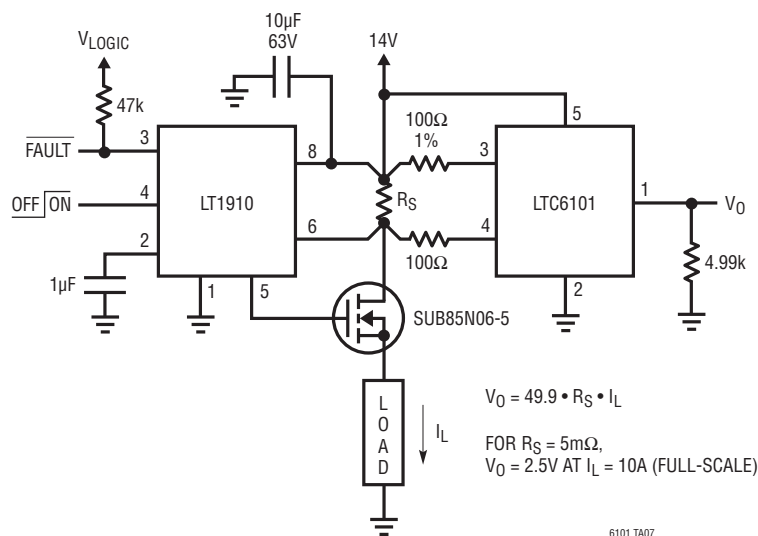
Figure 117. Intelligent High Side Switch

MOTORS AND INDUCTIVE LOADS

Relay Driver (Figure 118)

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 V_S 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 5A.

Full-Bridge Load Current Monitor (Figure 119)

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.

Figure 118. Relay Driver

Figure 119. Full-Bridge Load Current Monitor

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MOTORS AND INDUCTIVE LOADS

Bidirectional Current Sensing in H-Bridge Drivers (Figure 120)

Each channel of an LTC6103 provides measurement of the supply current into a half-bridge driver section. Since only one of the half-bridge sections will be conducting current in the measurable direction at any given time, only one output at a time will have a signal. Taken differentially, the two outputs form a bidirectional measurement for subsequent circuitry, such as an ADC. In this configuration, any load fault to ground will also be detected so that bridge protection can be implemented. This arrangement avoids the high frequency common mode rejection problem that can cause problems in "flying" sense resistor circuits.

*USE "SIGN-MAGNITUDE" PWM FOR ACCURATE
LOAD CURRENT CONTROL AND MEASUREMENT
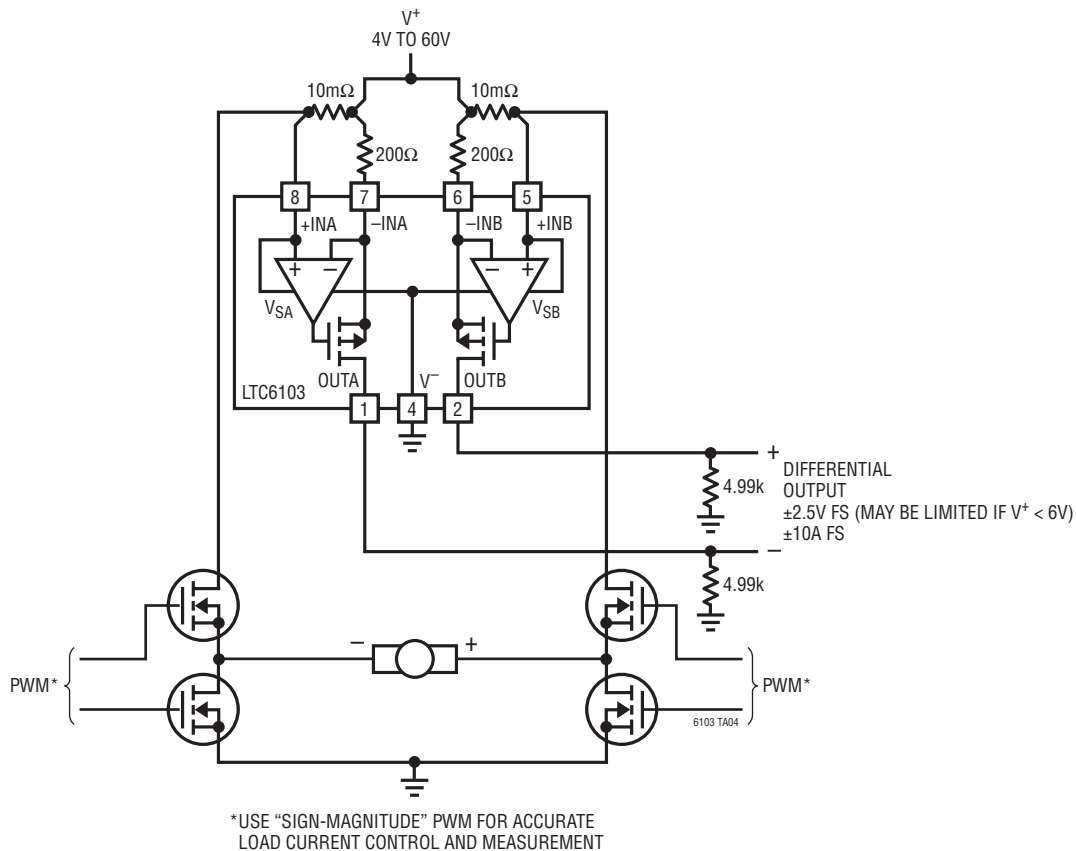
Figure 120. Bidirectional Current Sensing in H-Bridge Drivers

MOTORS AND INDUCTIVE LOADS

Single Output Provides 10A H-Bridge Current and Direction (Figure 121)

The output voltage of the LTC6104 will be above or below the external 2.5V reference potential depending on which side of the H-bridge is conducting current. Monitoring the current in the bridge supply lines eliminates fast voltage changes at the inputs to the sense amplifiers.

*USE "SIGN-MAGNITUDE" PWM FOR ACCURATE LOAD CURRENT CONTROL AND MEASUREMENT
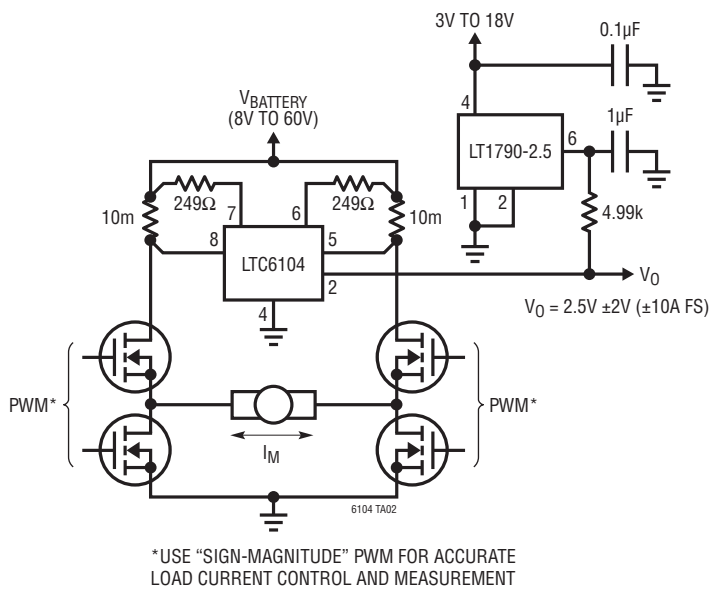
Figure 121. Single Output Provides 10A H-Bridge Current and Direction

Monitor Solenoid Current on the Low Side (Figure 122)

Driving an inductive load such as a solenoid creates large transients of common mode voltage at the inputs to a current sense amplifier. When de-energized the voltage across the solenoid reverses (also called the freewheel state) and tries to go above its power supply voltage but is clamped by the freewheel diode. The LT6105 senses the solenoid current continuously over an input voltage range of 0V to one diode drop above the 24V supply.

Monitor Solenoid Current on the High Side (Figure 123)

Driving an inductive load such as a solenoid creates large transients of common mode voltage at the inputs to a current sense amplifier. When de-energized the voltage
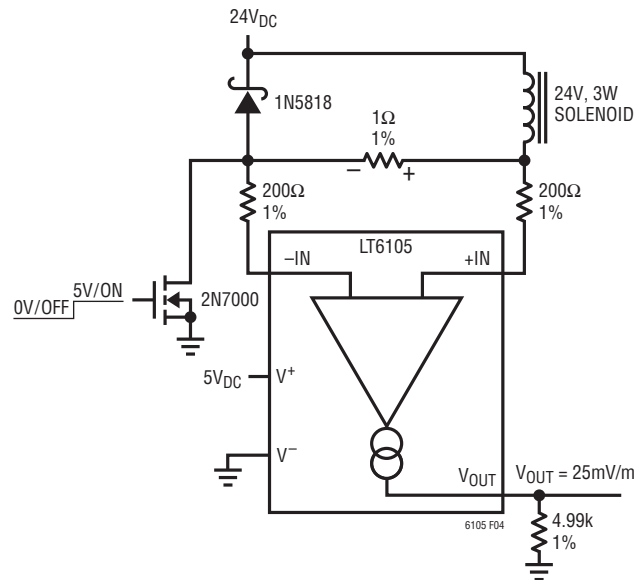
Figure 122. Monitor Solenoid Current on the Low Side
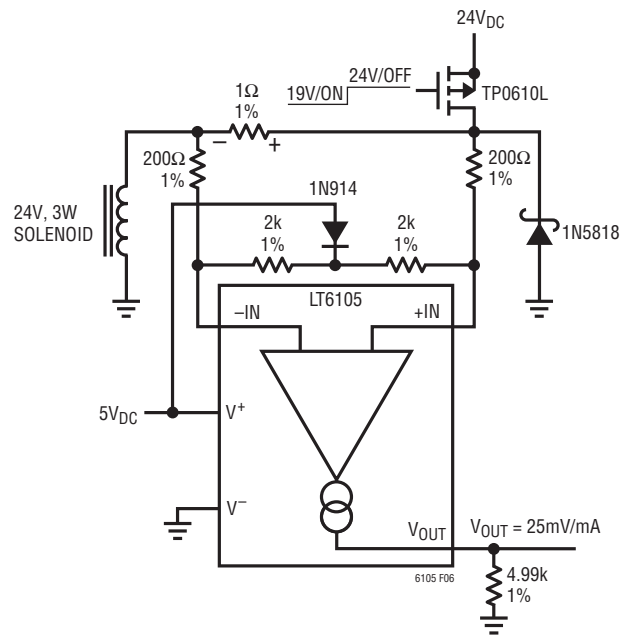
Figure 123. Monitor Solenoid Current on the High Side

across the solenoid reverses (also called the freewheel state) and tries to go below ground but is clamped by the freewheel diode. The LT6105 senses the solenoid current continuously with pull-up resistors keeping the inputs within the most accurate input voltage range.

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MOTORS AND INDUCTIVE LOADS

Monitor H-Bridge Motor Current Directly (Figures 124a and 124b)

The LT1999 is a differential input amplifier with a very wide, –5V to 80V, input common mode voltage range. With an AC CMRR greater than 80dB at 100kHz allows the direct measurement of the bidirectional current in an H-bridge driven load. The large and fast common mode input voltage swings are rejected at the output. The amplifier gain is fixed at 10, 20 or 50 requiring only a current sense resistor and supply bypass capacitors external to the amplifier.

Large Input Voltage Range for Fused Solenoid Current Monitoring (Figure 125)

The LT1999 has series resistors at each input. This allows the input to be overdriven in voltage without damaging the amplifier. The amplifier will monitor the current through the positive and negative voltage swings of a solenoid driver. The large differential input with a blown protective fuse will force the output high and not damage the LT1999.
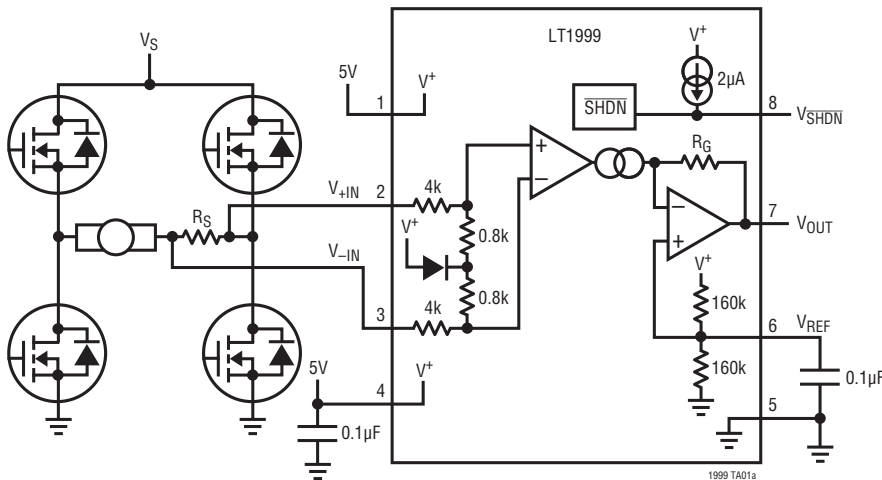
Figure 124a
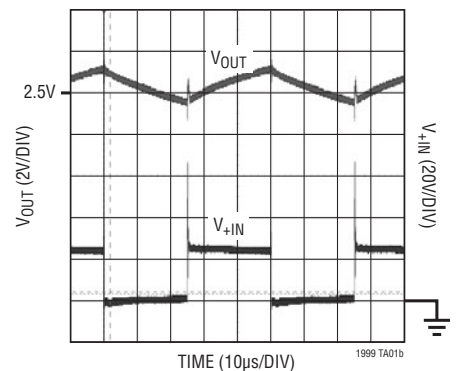
Figure 124b

Figure 124. Monitor H-Bridge Motor Current Directly
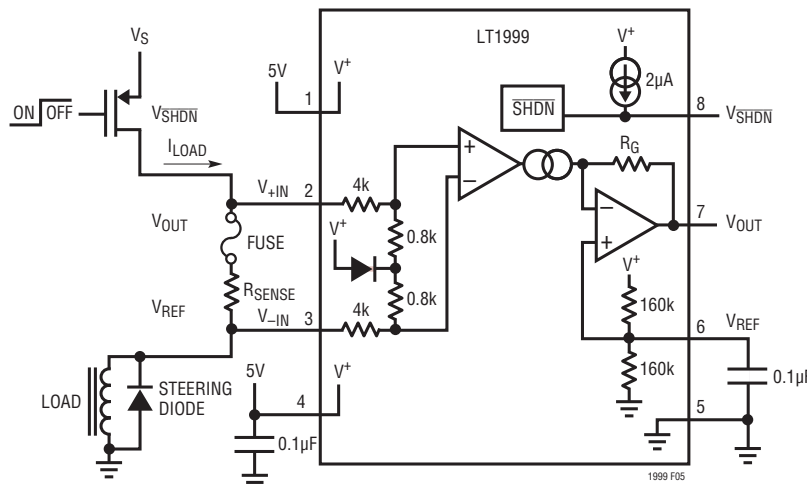
Figure 125. Large Input Voltage Range for Fused Solenoid Current Monitoring

MOTORS AND INDUCTIVE LOADS

Monitor Both the ON Current and the Freewheeling Current Through a High Side Driven Solenoid (Figure 126)

Placing the current sense resistor inside the loop created by a grounded solenoid and the freewheeling clamp diode allows for continuous monitoring of the solenoid current while being energized or switched OFF. The LT1999 operates accurately with an input common mode voltage down to –5V below ground.

Monitor Both the ON Current and the Freewheeling Current In a Low Side Driven Solenoid (Figure 127)

Placing the current sense resistor inside the loop created by a grounded solenoid and the freewheeling clamp diode allows for continuous monitoring of the solenoid current while being energized or switched OFF. The LT1999 operates accurately with an input common mode voltage up to 80V. In this circuit the input is clamped at one diode above the solenoid supply voltage.
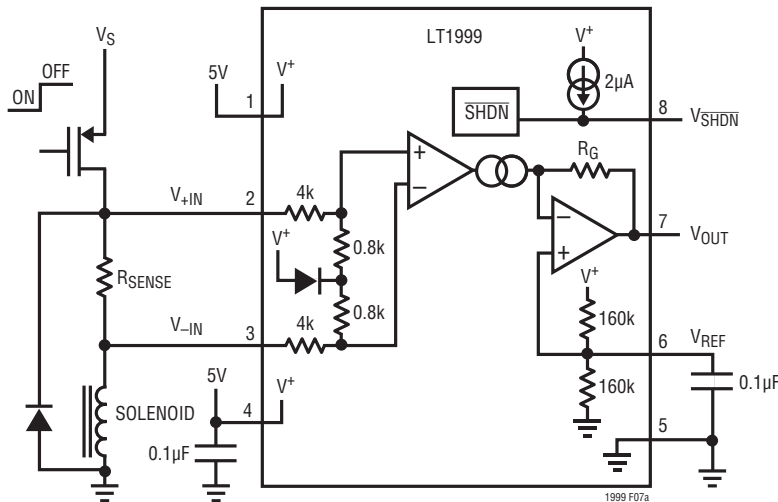
Figure 126. Monitor Both the ON Current and the Freewheeling Current Through a High Side Driven Solenoid
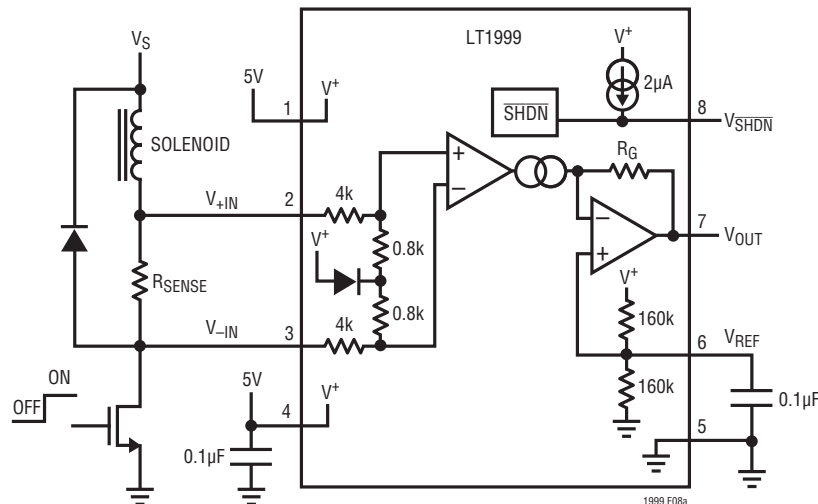
Figure 127. Monitor Both the ON Current and the Freewheeling Current In a Low Side Driven Solenoid

MOTORS AND INDUCTIVE LOADS

Fixed Gain DC Motor Current Monitor (Figure 128)

With no critical external components the LT1999 can be connected directly across a sense resistor in series with an H-bridge driven motor. The amplifier output voltage is referenced to one-half supply so the direction of motor rotation is indicated by the output being above or below the DC output voltage when stopped.
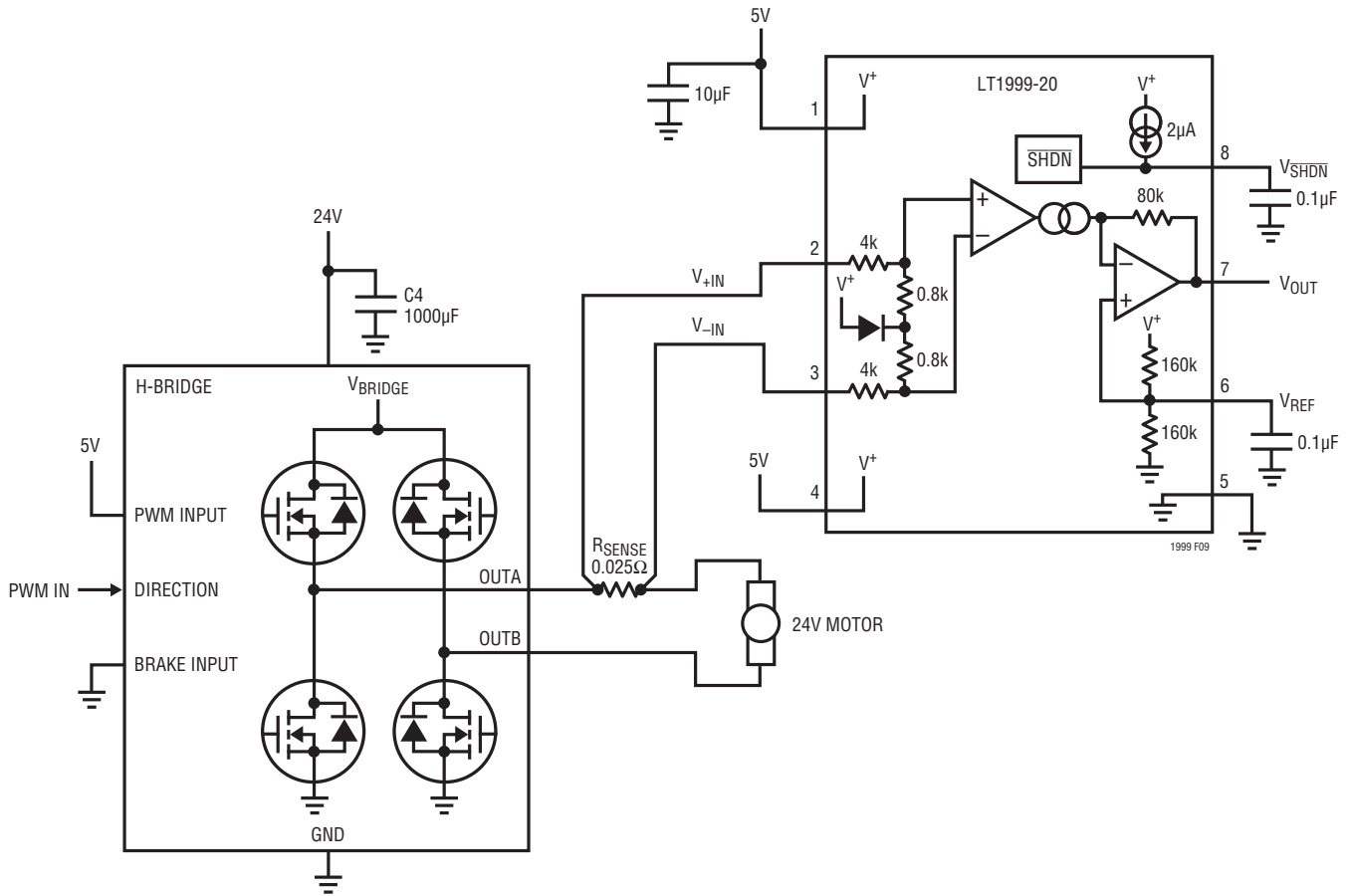
Figure 128. Fixed Gain DC Motor Current Monitor

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MOTORS AND INDUCTIVE LOADS

Simple DC Motor Torque Control (Figure 129)

The torque of a spinning motor is directly proportional to the current through it. In this circuit the motor current is monitored and compared to a DC set point voltage. The motor current is sensed by an LT6108-1 and forced to match the set point current value through an amplifier and a PWM motor drive circuit. The LTC6992-1 produces a PWM signal from 0% to 100% duty cycle for a 0V to 1V change at the MOD input pin.
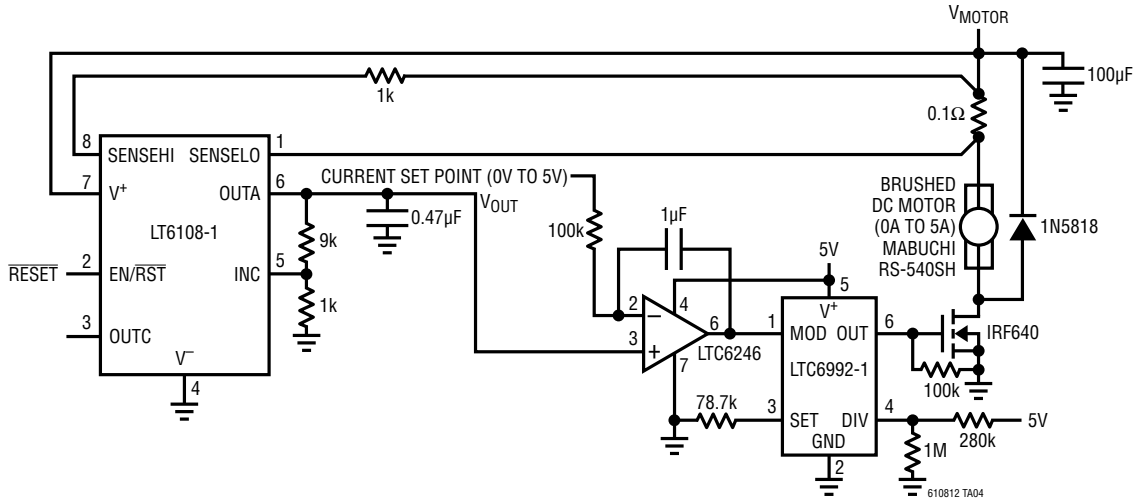
Figure 129. Simple DC Motor Torque Control

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MOTORS AND INDUCTIVE LOADS

Small Motor Protection and Control (Figure 130)

DC motor operating current and temperature can be digitized and sent to a controller which can then adjust the applied control voltage. Stalled rotor or excessive loading on the motor can be sensed.

Large Motor Protection and Control (Figure 131)

For high voltage/current motors, simple resistor dividers can scale the signals applied to an LTC2990 14-bit converter. Proportional DC motor operating current and temperature can be digitized and sent to a controller which can then adjust the applied control voltage. Stalled rotor or excessive loading on the motor can be sensed.

CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x59

T_{AMB}	REG 4, 5	0.0625°C/LSB
I_{MOTOR}	REG 6, 7	194µA/LSB
T_{MOTOR}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

VOLTAGE AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V_{MOTOR}	REG 8, 9	305.18µVLSB
T_{MOTOR}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB
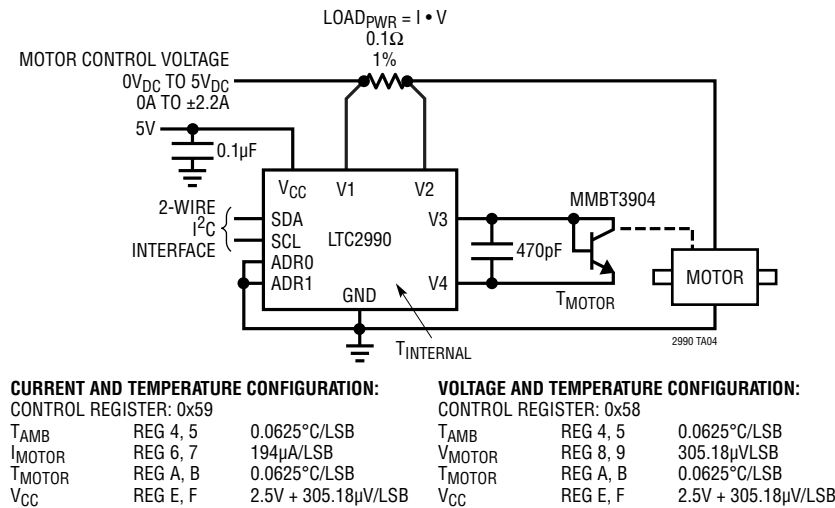
Figure 130. Small Motor Protection and Control

VOLTAGE AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V_{MOTOR}	REG 8, 9	2.44mVLSB
T_{MOTOR}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x59

T_{AMB}	REG 4, 5	0.0625°C/LSB
I_{MOTOR}	REG 6, 7	15.54mA/LSB
T_{MOTOR}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB
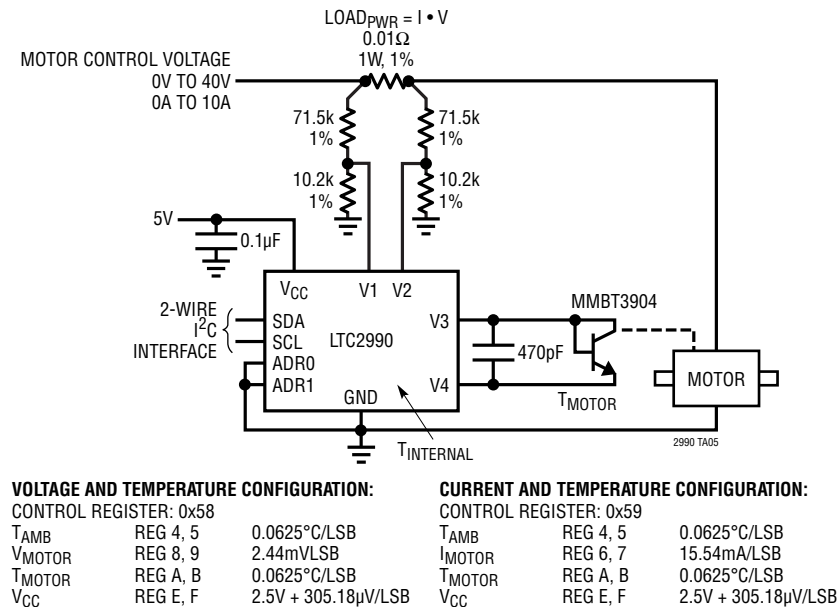
Figure 131. Large Motor Protection and Control

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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.

Input Remains Hi-Z when LT6100 is Powered Down (Figure 132)

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 1µA of current. This is due to an implementation of Linear Technology's Over-The-Top input technique at its front end.
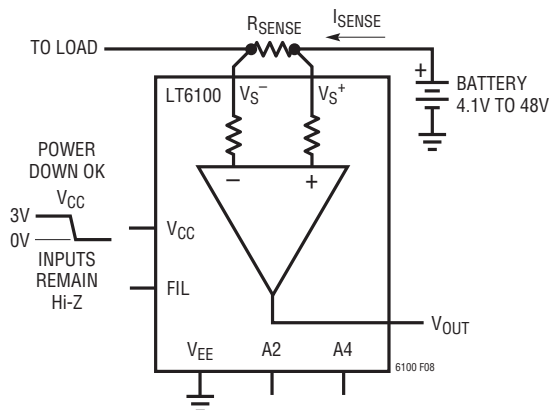
Figure 132. Input Remains Hi-Z when LT6100 is Powered Down

Charge/Discharge Current Monitor on Single Supply with Shifted V$_{BIAS}$ (Figure 133)

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.
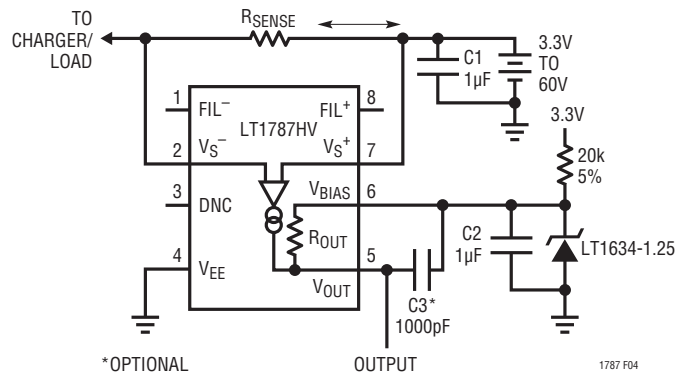
Figure 133. Charge/Discharge Current Monitor on Single Supply with Shifted V$_{BIAS}$

Battery Current Monitor (Figure 134)

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.

$$V_O = I_L \left(\frac{R_B}{R_A}\right) R_{SENSE}$$

FOR R$_A$ = 1k, R$_B$ = 10k

$$\frac{V_O}{I_L} = 1V/A$$
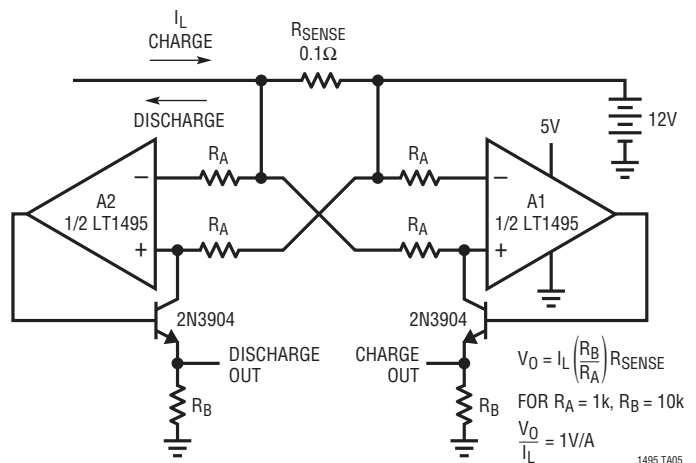
Figure 134. Battery Current Monitor

BATTERIES

Input Current Sensing Application (Figure 135)

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.

Figure 135. Input Current Sensing Application

Coulomb Counter (Figure 136)

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 and INT connected together) the pulses are approximately 1μs wide and around 1Hz full-scale.

Figure 136. Coulomb Counter

Li-Ion Gas Gauge (Figure 137)

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.

NiMH Charger (Figure 138)

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.

BATTERIES

Figure 137. Li-Ion Gas Gauge

Figure 138. NiMH Charger

BATTERIES

Single Cell Li-Ion Charger (Figure 139)

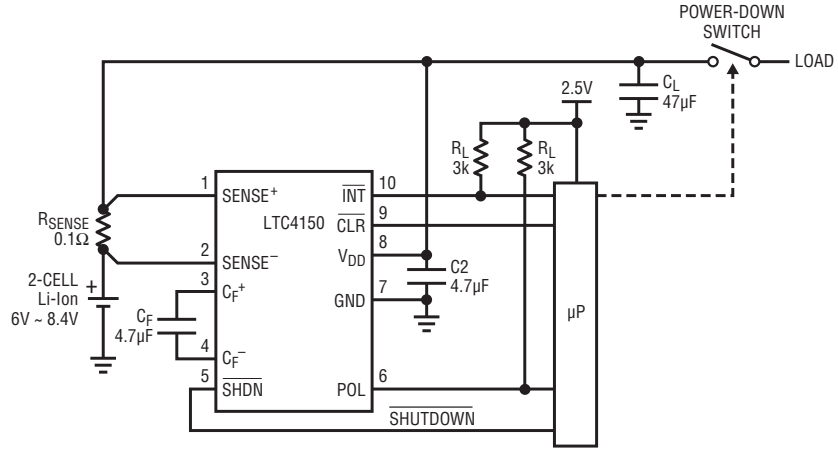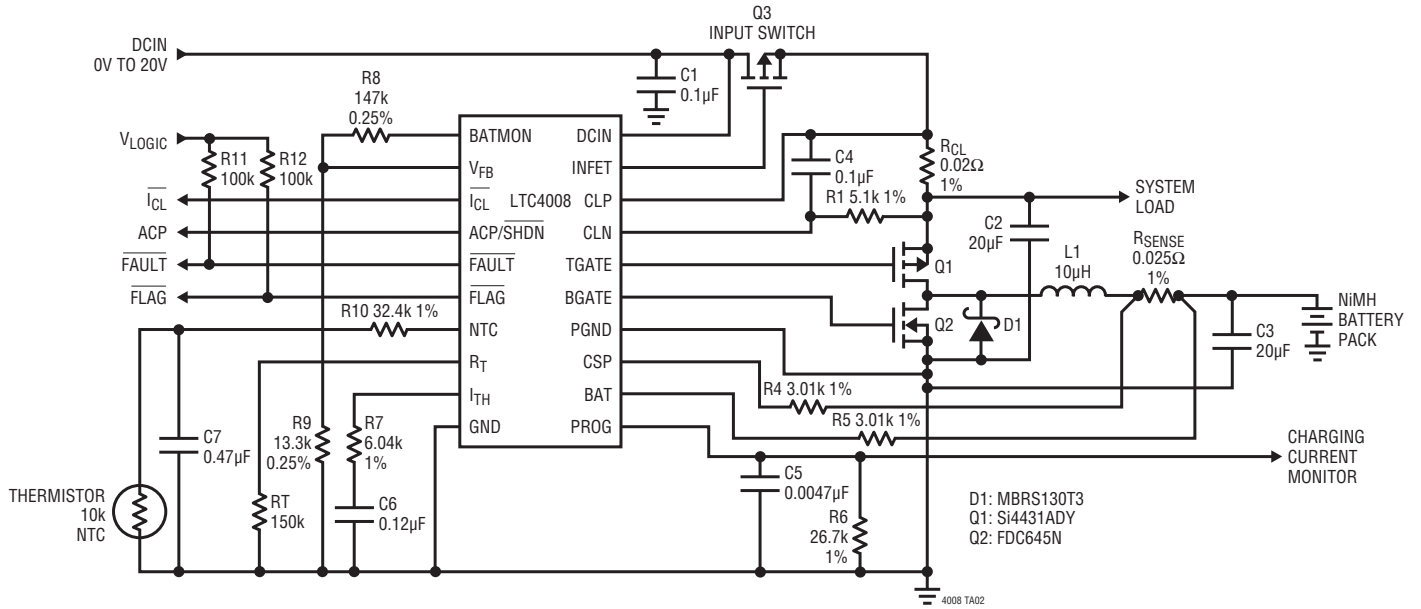Controlling the current flow in lithium-ion battery chargers is essential for safety and extending useful battery life. Intelligent battery charger ICs can be used in fairly simple circuits to monitor and control current, voltage and even battery pack temperature for fast and safe charging.

Li-Ion Charger (Figure 140)

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.

Battery Monitor (Figure 141)

Op amp sections A and B form classical high side sense circuits in conjunction with Q1 and 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 indicating 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.
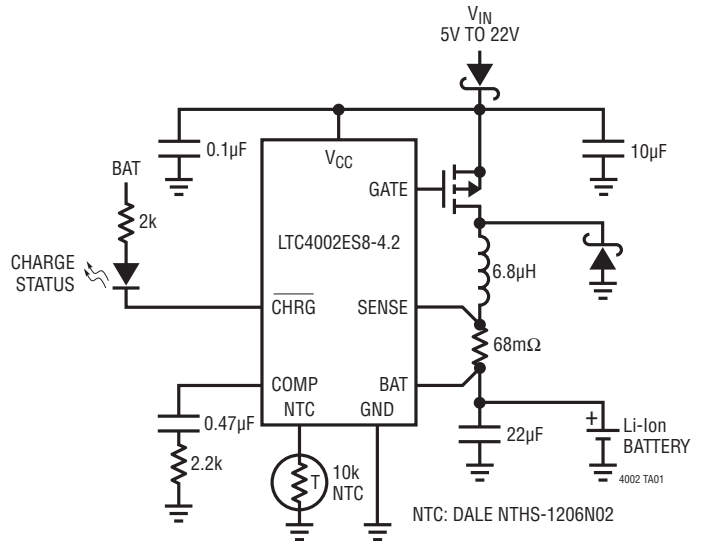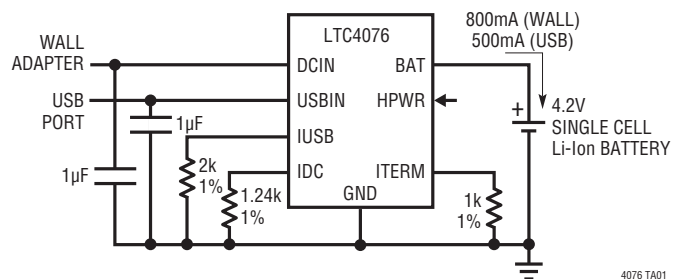

Figure 139. Single Cell Li-Ion Charger

Figure 140. Li-Ion Charger

$$|I_{BATT}| = \frac{V_{OUT}}{(R_S)(R_G/R_A)(GAIN)} = \frac{V_{OUT}}{GAIN} \text{ AMPS}$$
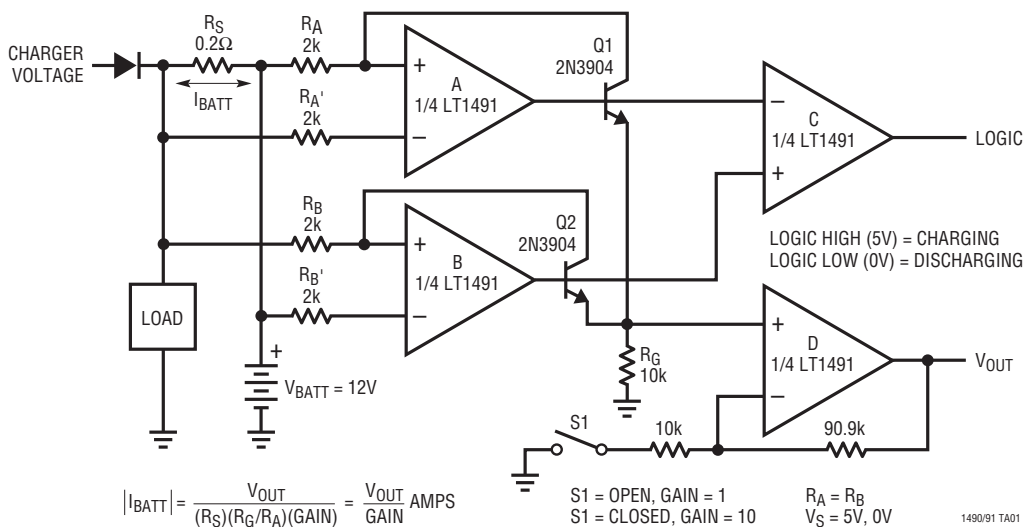
Figure 141. Battery Monitor

BATTERIES

<div style="display: flex; gap: 2em;">

<div style="flex: 1;">

Monitor Charge and Discharge Currents at One Output (Figure 142)

Current from a battery to a load or from a charger to the battery can be monitored using a single sense resistor and the LTC6104. Discharging load current will source a current at the output pin in proportion to the voltage across the sense resistor. Charging current into the battery will sink a current at the output pin. The output voltage above or below the voltage V_{REF} will indicate charging or discharging of the battery.

</div>

<div style="flex: 1;">

Battery Stack Monitoring (Figure 143)

The comparators used in the LT6109 can be used separately. In this battery stack monitoring circuit a low on either comparator output will disconnect the load from the battery. One comparator watches for an overcurrent condition (800mA) and the other for a low voltage condition (30V). These threshold values are fully programmable using resistor divider networks.

</div>

</div>

Figure 142. Monitor Charge and Discharge Currents at One Output
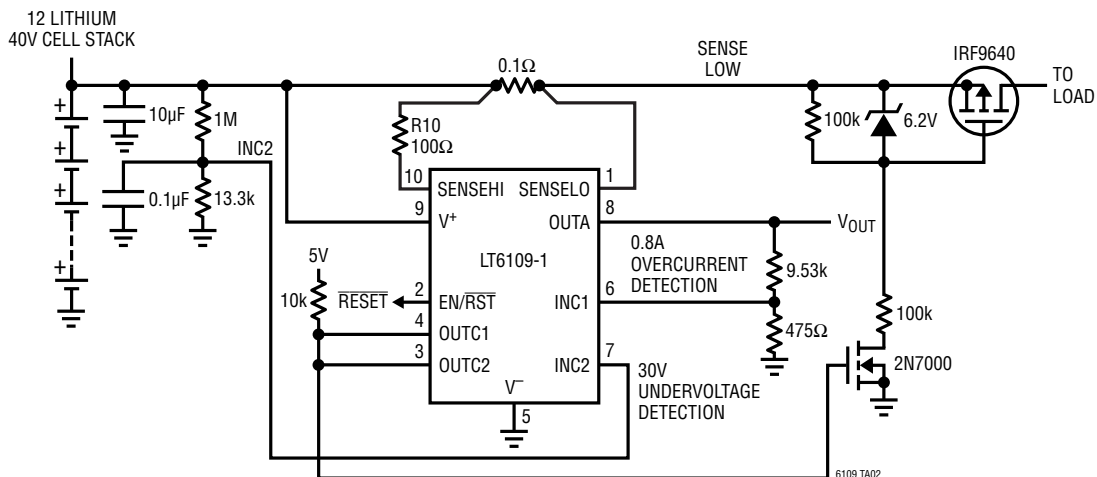
Figure 143. Battery Stack Monitoring

LINEAR TECHNOLOGY

BATTERIES

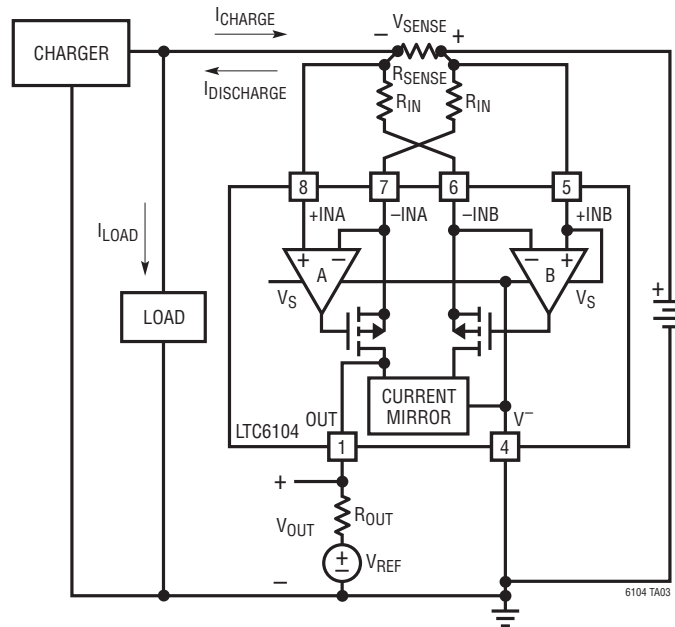## Coulomb Counting Battery Gas Gauge (Figure 144)

The LTC4150 converts the voltage across a sense resistor to a microprocessor interrupt pulse train. The time between each interrupt pulse is directly proportional to the current flowing through the sense resistor and therefore the number of coulombs travelling to or from the battery power source. A polarity output indicates the direction of current flow. By counting interrupt pulses with the polarity adding or subtracting from the running total, an indication of the total change in charge on a battery is determined. This acts as a battery gas gauge to indicate where the battery charge is between full or empty.

High Voltage Battery Coulomb Counting (Figure 145)

When coulomb counting, after each interrupt interval the internal counter needs to be cleared for the next time interval. This can be accomplished by the µP or the LTC4150 can clear itself. In this circuit the IC is powered from a battery supply which is at a higher voltage than the interrupt counting µP supply.
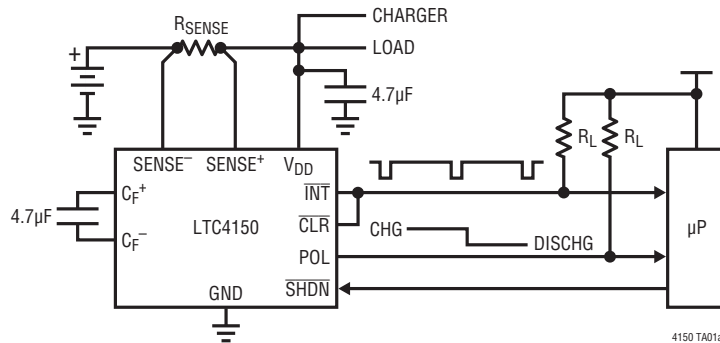
Figure 144. Coulomb Counting Battery Gas Gauge
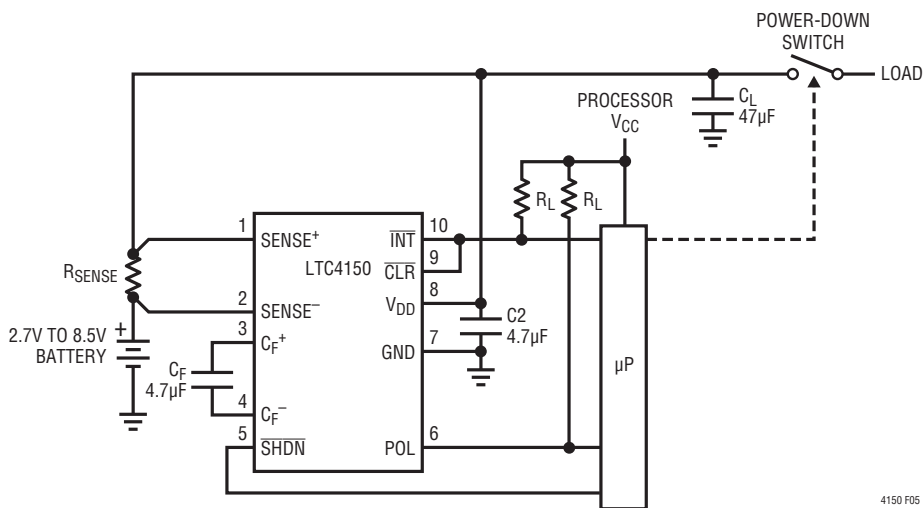
Figure 145. High Voltage Battery Coulomb Counting

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BATTERIES

Low Voltage Battery Coulomb Counting (Figure 146)

When coulomb counting, after each interrupt interval the internal counter needs to be cleared for the next time interval. This can be accomplished by the µP or the LTC4150 can clear itself. In this circuit the IC is powered from a battery supply which is at a lower voltage than the interrupt counting µP supply. The CLR signal must be attenuated because the INT pin is pulled to a higher voltage.

Single Cell Lithium-Ion Battery Coulomb Counter (Figure 147)

This is a circuit which will keep track of the total change in charge of a single cell Li-Ion battery power source. The maximum battery current is assumed to be 500mA due to the 50mV full-scale sense voltage requirement of the LTC4150. The µP supply is greater than the battery supply.
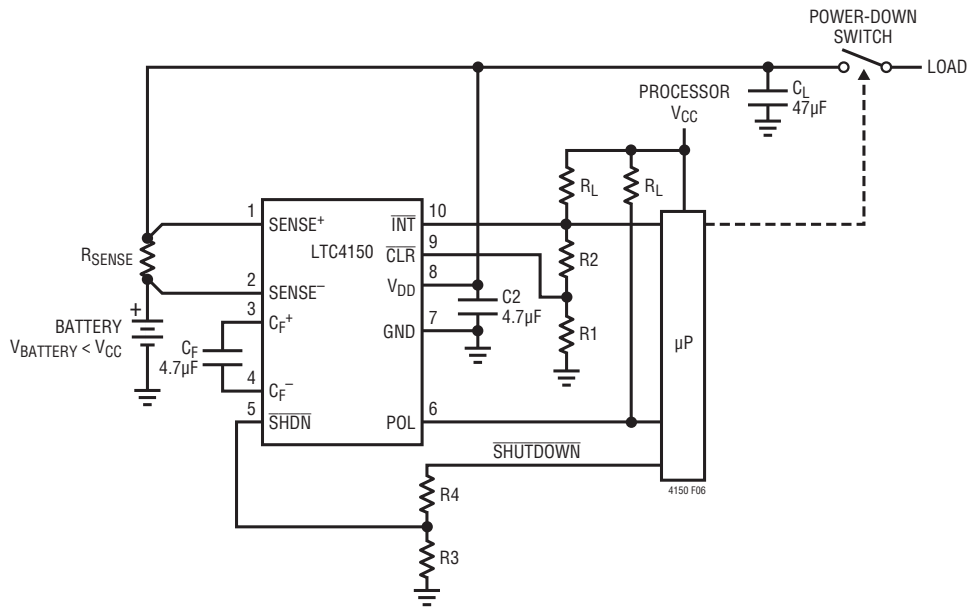
Figure 146. Low Voltage Battery Coulomb Counting
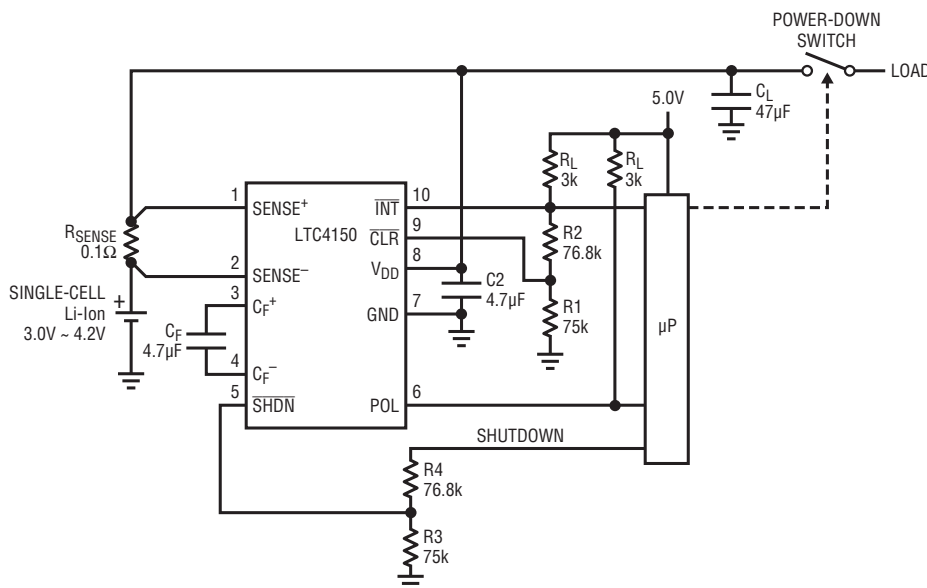
Figure 147. Single Cell Lithium-Ion Battery Coulomb Counter

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BATTERIES

Complete Single Cell Battery Protection (Figure 148)

Voltage, current and battery temperature can all be monitored by a single LTC2990 ADC to 14-bit resolution. Each of these parameters can detect an excessive condition and signal the termination or initiation of cell charging. The ADC can be continually reconfigured for single-ended or differential measurements to produce the required information.


VOLTAGE AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V_{BAT}	REG 8, 9	305.18µVLSB
T_{BAT}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x59

T_{AMB}	REG 4, 5	0.0625°C/LSB
I_{BAT}	REG 6, 7	1.295mA/LSB
T_{BAT}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB
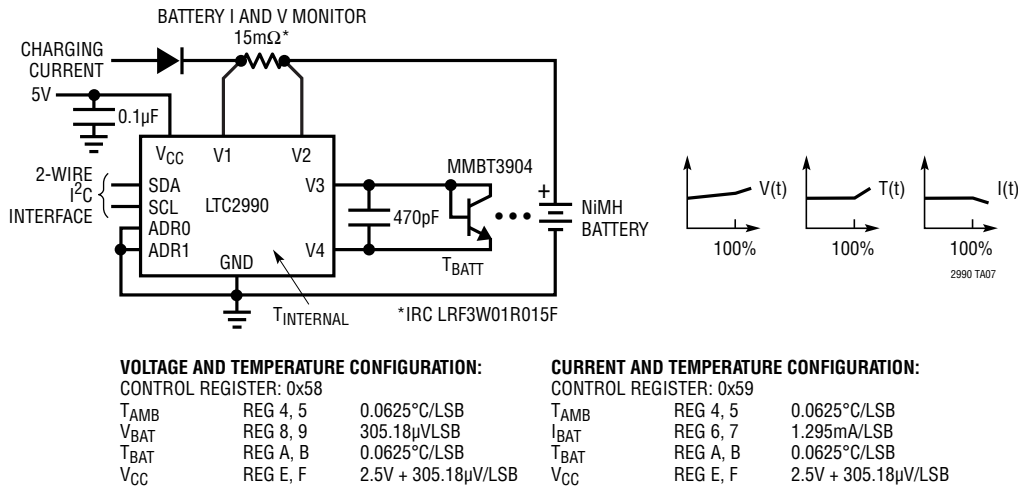
Figure 148. Complete Single Cell Battery Protection

More Battery Circuits Are Shown in Other Chapters:

FIGURE	TITLE
21	Sensed Current Includes Monitor Circuit Supply Current
58	Bidirectional Precision Current Sensing
179	Digitizing Charging and Loading Current in a Battery Monitor
181	Ampere-Hour Gauge
209	Use Kelvin Connections to Maintain High Current Accuracy
216	Dual Sense Amplifier Can Have Different Sense Resistors and Gain

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.

Fast Compact –48V Current Sense (Figure 149)

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 (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.

Conventional H-Bridge Current Monitor (Figure 150)

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.
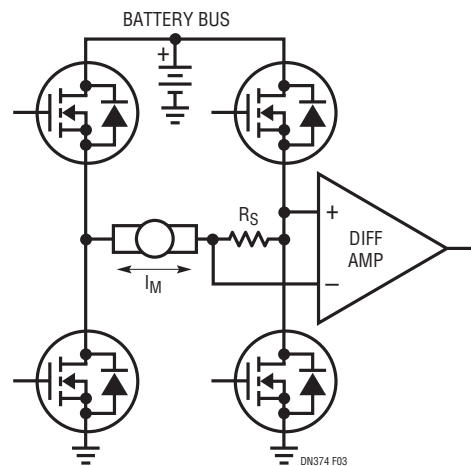

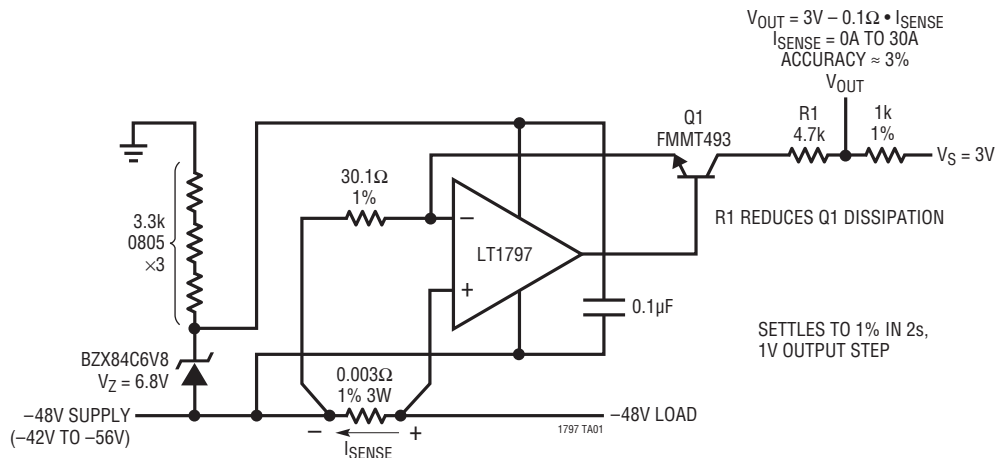**Figure 150. Conventional H-Bridge Current Monitor**

Figure 149. Fast Compact –48V Current Sense

HIGH SPEED

Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter (Figure 151)

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 (Figure 152)

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.
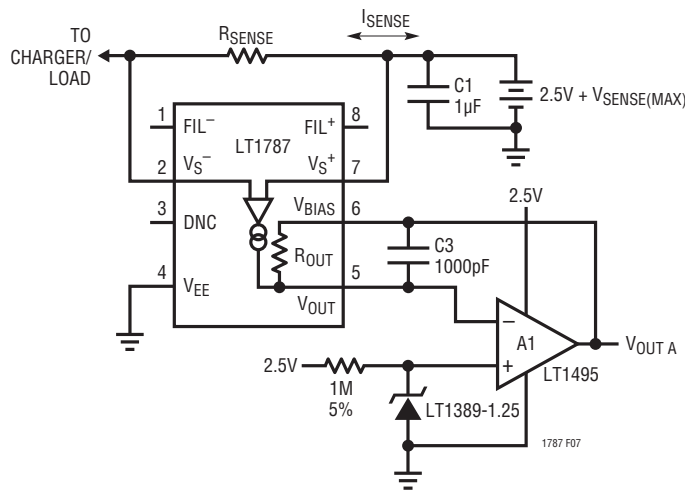

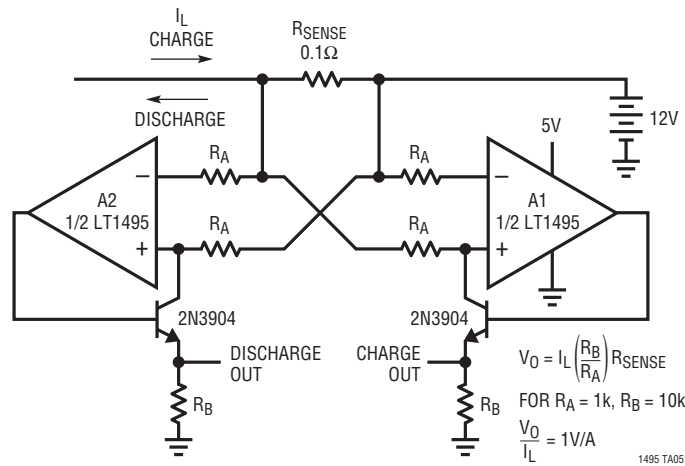Figure 151. Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter

Figure 152. Battery Current Monitor

HIGH SPEED

Fast Current Sense with Alarm (Figure 153)

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/A from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/µs 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 overcurrent flag. With the 400mV reference the flag occurs at 4A.

Fast Differential Current Source (Figure 154)

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.
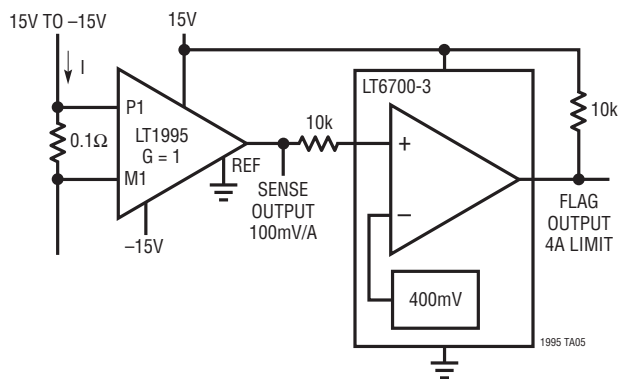
Figure 153. Fast Current Sense with Alarm

$$I_{OUT} = \frac{V_{IN2} - V_{IN1}}{R}$$

*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 = $\frac{I_{OUTP-P} \cdot R_L}{2}$
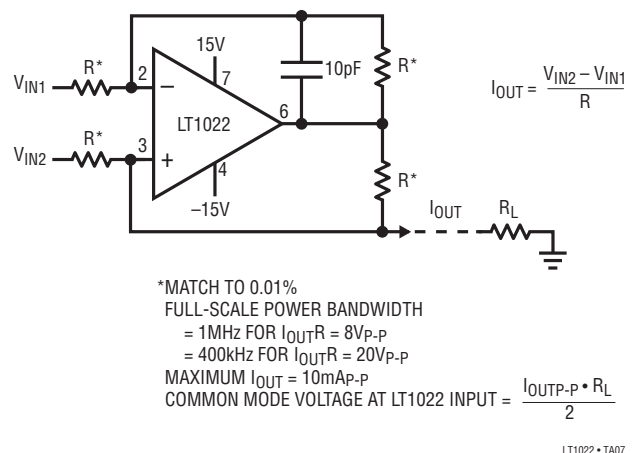
Figure 154. Fast Differential Current Source

More High Speed Circuits Are Shown in Other Chapters:

FIGURE	TITLE
22	Wide Voltage Range Current Sensing
124	Monitor H-Bridge Motor Current Directly
128	Fixed Gain DC Motor Current Monitor
143	Battery Stack Monitoring
168	Monitoring a Fuse Protected Circuit
169	Circuit Fault Protection with Early Warning and Latching Load Disconnect
170	Use Comparator Output to Initialize Interrupt Routines

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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.

High Side Current Sense and Fuse Monitor (Figure 155)

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 1µA max from the battery bus.
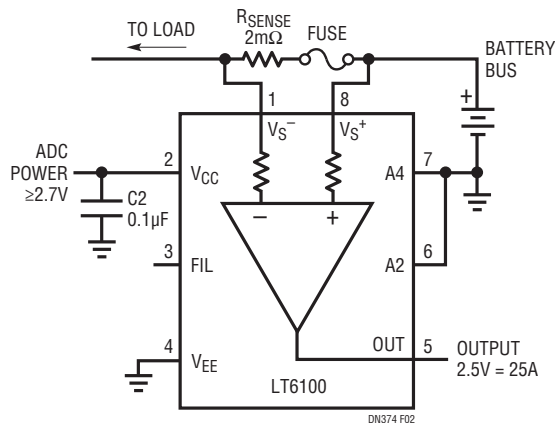

Figure 155. High Side Current Sense and Fuse Monitor

Schottky Prevents Damage During Supply Reversal (Figure 156)

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.
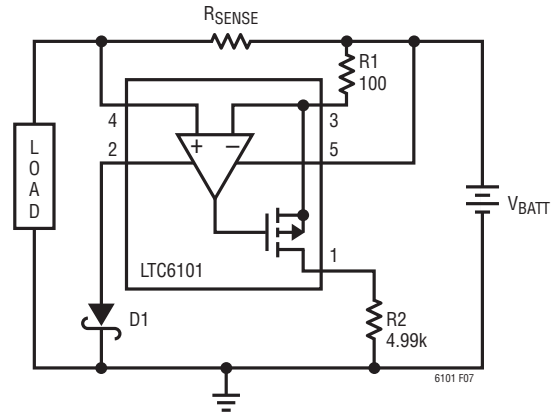
Figure 156. Schottky Prevents Damage During Supply Reversal

Additional Resistor R3 Protects Output During Supply Reversal (Figure 157)

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.

Figure 157. Additional Resistor R3 Protects Output During Supply Reversal

Electronic Circuit Breaker (Figure 158)

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

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FAULT SENSING

Figure 158. Electronic Circuit Breaker

Electronic Circuit Breaker (Figure 159)

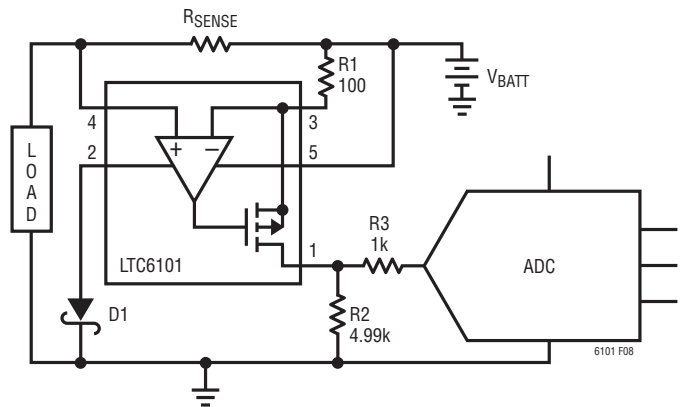The LTC1153 is an electronic circuit breaker. Sensed current to a load opens the breaker when 100mV is developed between the supply input, V_S, and the drain sense pin, DS. To avoid transient, or nuisance trips of the break components RD and CD delay the action for 1ms. A thermistor can also be used 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 reconnect the load after 200ms using the 0.22µF timer capacitor shown.

1.25V Electronic Circuit Breaker (Figure 160)

The LTC4213 provides protection and automatic circuit breaker action by sensing drain-to-source voltage drop across the N-MOSFET. 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.

ALL COMPONENTS SHOWN ARE SURFACE MOUNT.
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 ** RL2006-100-70-30-PT1 KEYSTONE CARBON COMPANY (814) 781-1591

Figure 159. Electronic Circuit Breaker

Figure 160. 1.25V Electronic Circuit Breaker

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FAULT SENSING

Lamp Outage Detector (Figure 161)

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
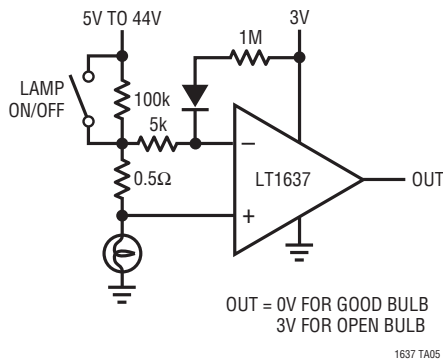
the op amp, so part substitutions are discouraged (however, this same circuit also works properly with an LT1716 comparator, also an Over-the-Top part).

Simple Telecom Power Supply Fuse Monitor (Figure 162)

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 (Figure 163)

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.
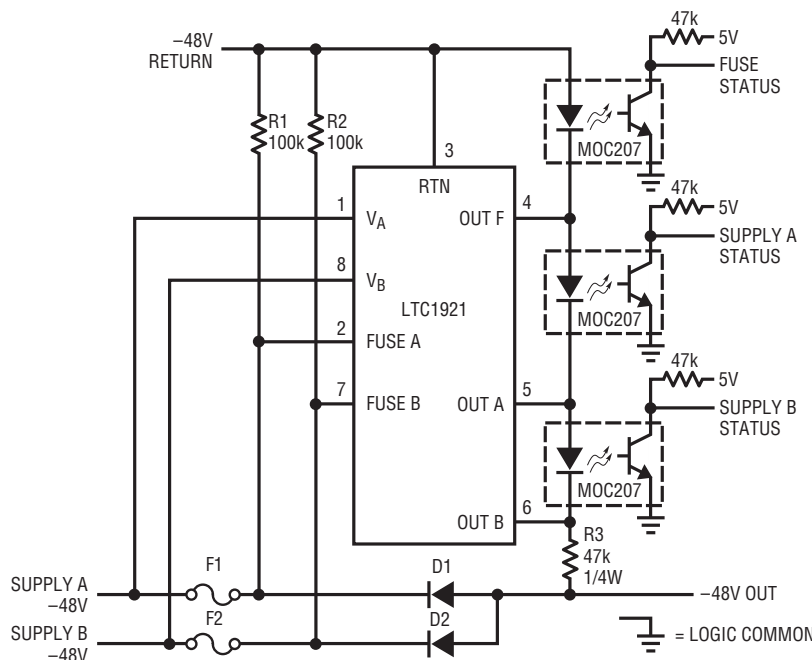

OUT = 0V FOR GOOD BULB
3V FOR OPEN BULB

1637 TA05

Figure 161. Lamp Outage Detector

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
$= V_A$	$\neq V_B$	1
$\neq V_A$	$= V_B$	1
$\neq V_A$	$\neq V_B$	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

Figure 162. Simple Telecom Power Supply Fuse Monitor

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FAULT SENSING

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.
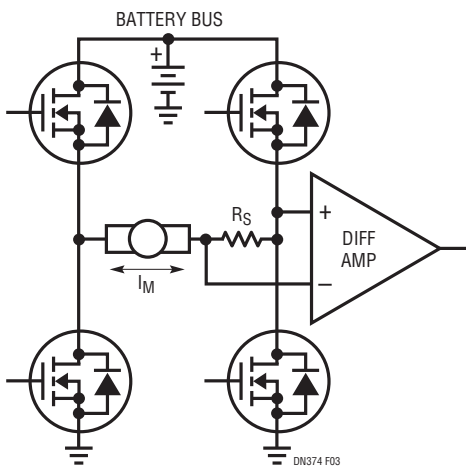

Figure 163. Conventional H-Bridge Current Monitor

Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter (Figure 164)

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.
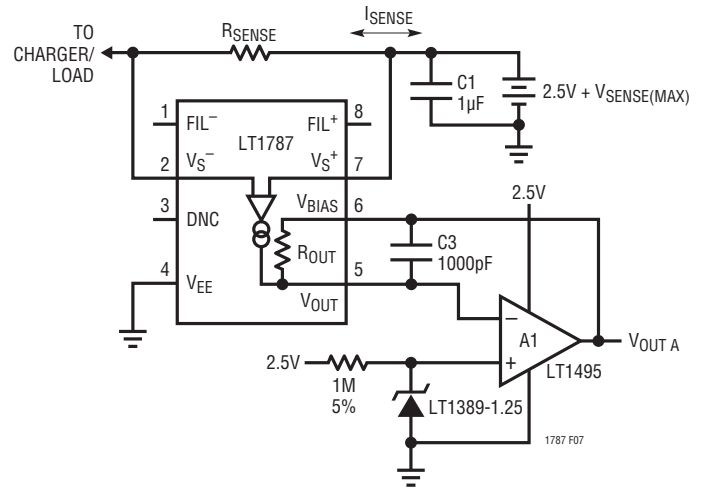

Figure 164. Single-Supply 2.5V Bidirectional Operation with External Voltage Reference and I/V Converter

Battery Current Monitor (Figure 165)

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.
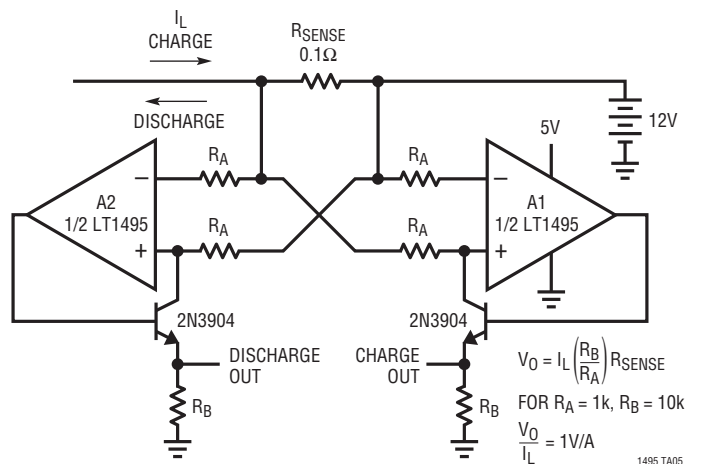

$$V_O = I_L \left(\frac{R_B}{R_A} \right) R_{SENSE}$$

FOR R_A = 1k, R_B = 10k

$$\frac{V_O}{I_L} = 1V/A$$

Figure 165. Battery Current Monitor

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FAULT SENSING

Fast Current Sense with Alarm (Figure 166)

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/A from the voltage across the 100mΩ sense resistor. With 32MHz of bandwidth and 1000V/µs 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 overcurrent flag. With the 400mV reference the flag occurs at 4A.
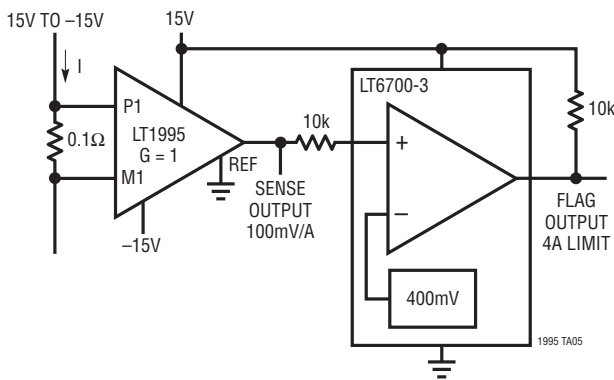

Figure 166. Fast Current Sense with Alarm

Monitor Current in an Isolated Supply Line (Figure 167)

Using the current sense amplifier output current to directly modulate the current in a photo diode is a simple method to monitor an isolated 48V industrial/telecom power supply. Current faults can be signaled to nonisolated monitoring circuitry.

Monitoring a Fuse Protected Circuit (Figure 168)

Current sensing a supply line that has a fuse for overcurrent protection requires a current sense amplifier with a wide differential input voltage rating. Should the fuse blow open the full load supply voltage appears across the inputs to the sense amplifier. The LT6105 can work with input voltage differentials up to 44V. The LT6105 output slews at 2V/µs so can respond quickly to fast current changes. When the fuse opens the LT6105 output goes high and stays there.
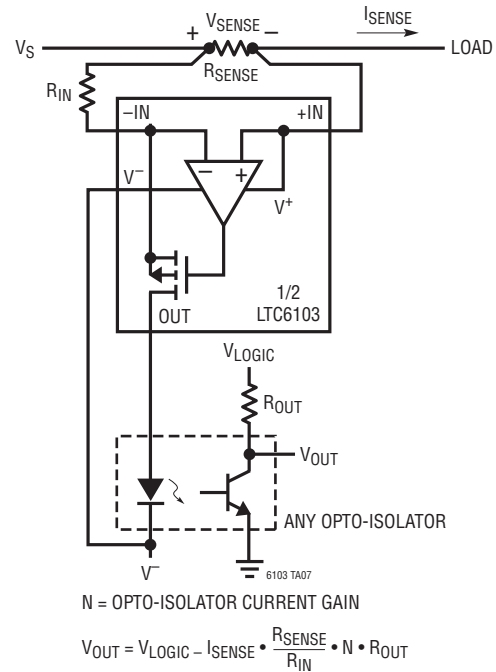

N = OPTO-ISOLATOR CURRENT GAIN

$$V_{OUT} = V_{LOGIC} - I_{SENSE} \cdot \frac{R_{SENSE}}{R_{IN}} \cdot N \cdot R_{OUT}$$

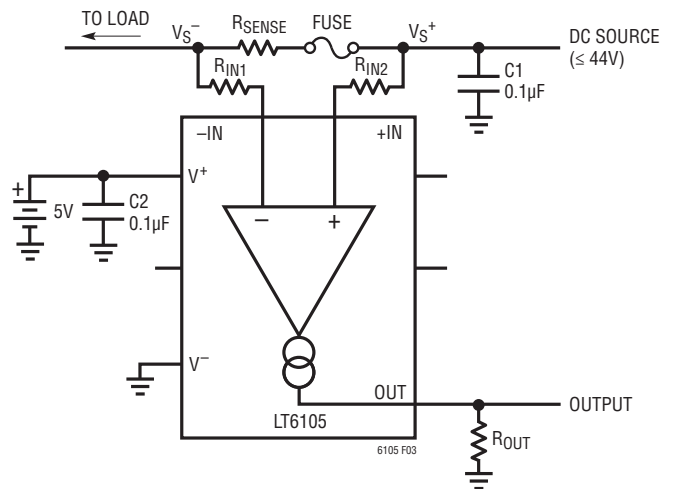Figure 167. Monitor Current in an Isolated Supply Line

Figure 168. Monitoring a Fuse Protected Circuit

FAULT SENSING

Circuit Fault Protection with Early Warning and Latching Load Disconnect (Figure 169)

With a precision current sense amplifier driving two built in comparators, LT6109-2 can provide current overload protection to a load circuit. The internal comparators have a fixed 400mV reference. The current sense output is resistor divided down so that one comparator will trip at an early warning level and the second at a danger level of current to the load (100mA and 250mA in this example). The comparator outputs latch when tripped so they can be used as a circuit breaker to disconnect and protect the load until a reset pulse is provided.

Use Comparator Output to Initialize Interrupt Routines (Figure 170)

The comparator outputs can connect directly to I/O or interrupt inputs to any microcontroller. A low level at OUTC2 can indicate an undercurrent condition while a low level at OUTC1 indicates an overcurrent condition. These interrupts force service routines in the microcontroller.
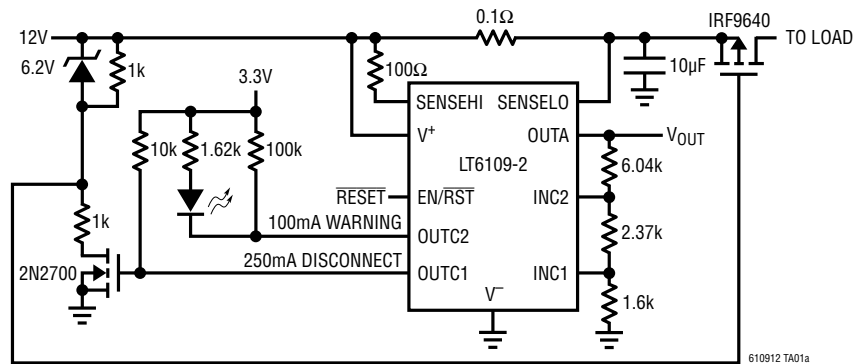

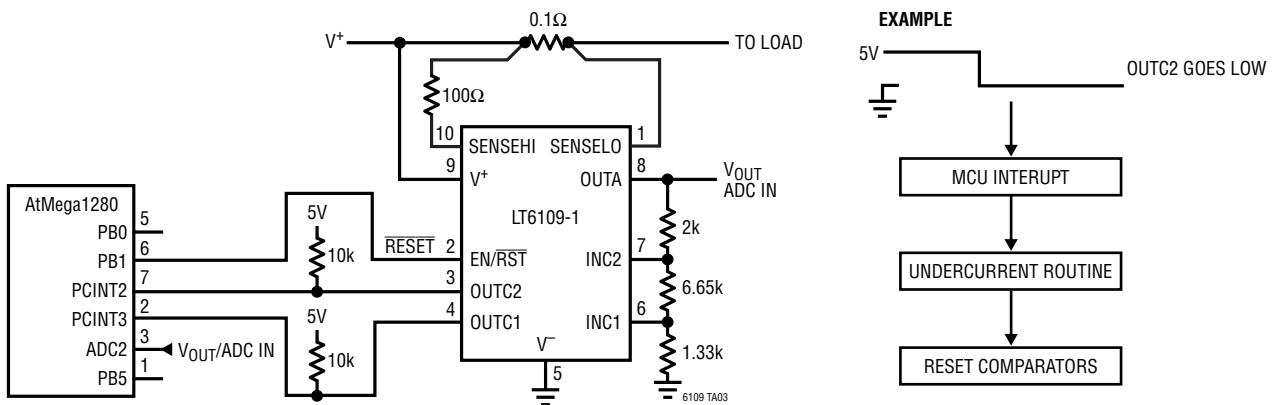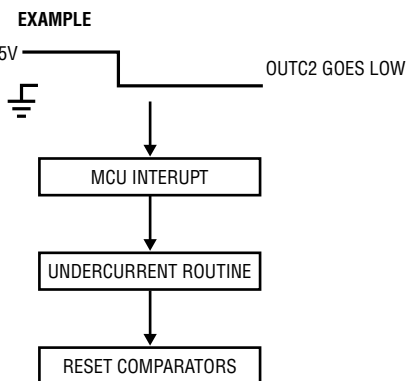Figure 169. Circuit Fault Protection with Early Warning and Latching Load Disconnect

Figure 170. Use Comparator Output to Initialize Interrupt Routines

an105fa

FAULT SENSING

Current Sense with Overcurrent Latch and Power-On Reset with Loss of Supply (Figure 171)

The LT6801-2 has a normal nonlatching comparator built in. An external logic gate configured in a positive feedback arrangement can create a latching output when an overcurrent condition is sensed. The same logic gate can also generate an active low power-on reset signal.
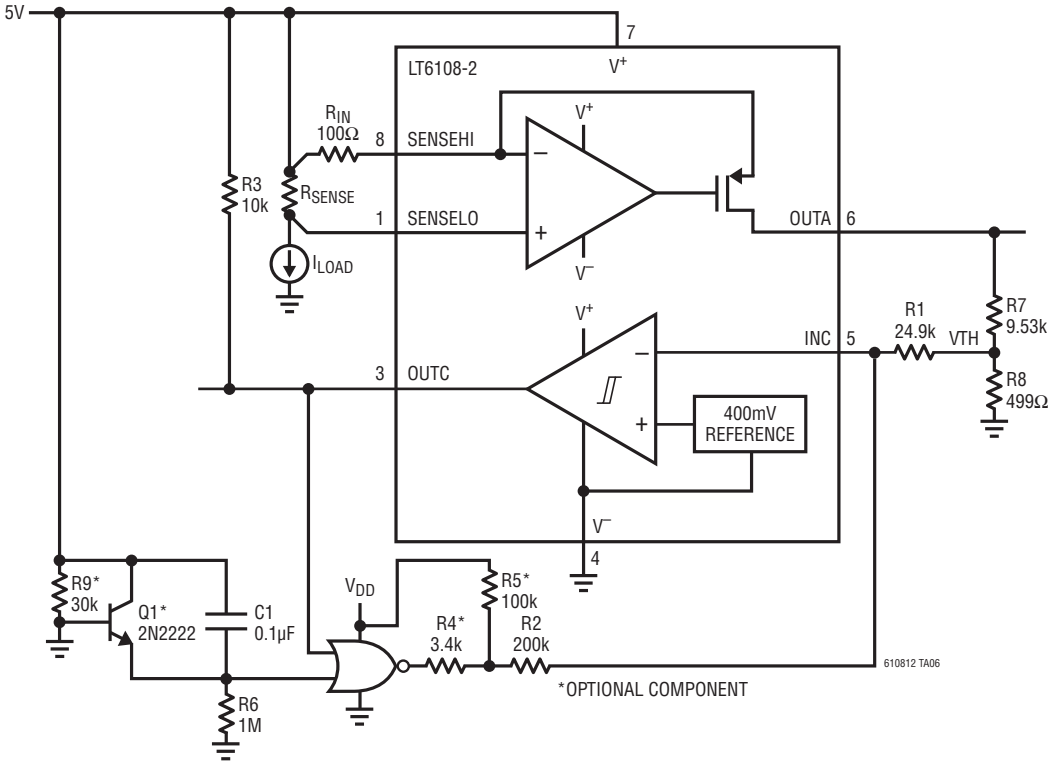

Figure 171. Current Sense with Overcurrent Latch and Power-On Reset with Loss of Supply

FAULT SENSING

More Fault Sensing Circuits Are Shown in Other Chapters:

FIGURE	TITLE
120	Bidirectional Current Sensing in H-Bridge Drivers
125	Large Input Voltage Range for Fused Solenoid Current Monitoring
136	Coulomb Counting Battery Gas Gauge
143	Battery Stack Monitoring
145	High Voltage Battery Coulomb Counting
146	Low Voltage Battery Coulomb Counting
147	Single Cell Lithium-Ion Battery Coulomb Counter
211	Power Intensive Circuit Board Monitoring

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.

Sensing Output Current (Figure 172)

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.
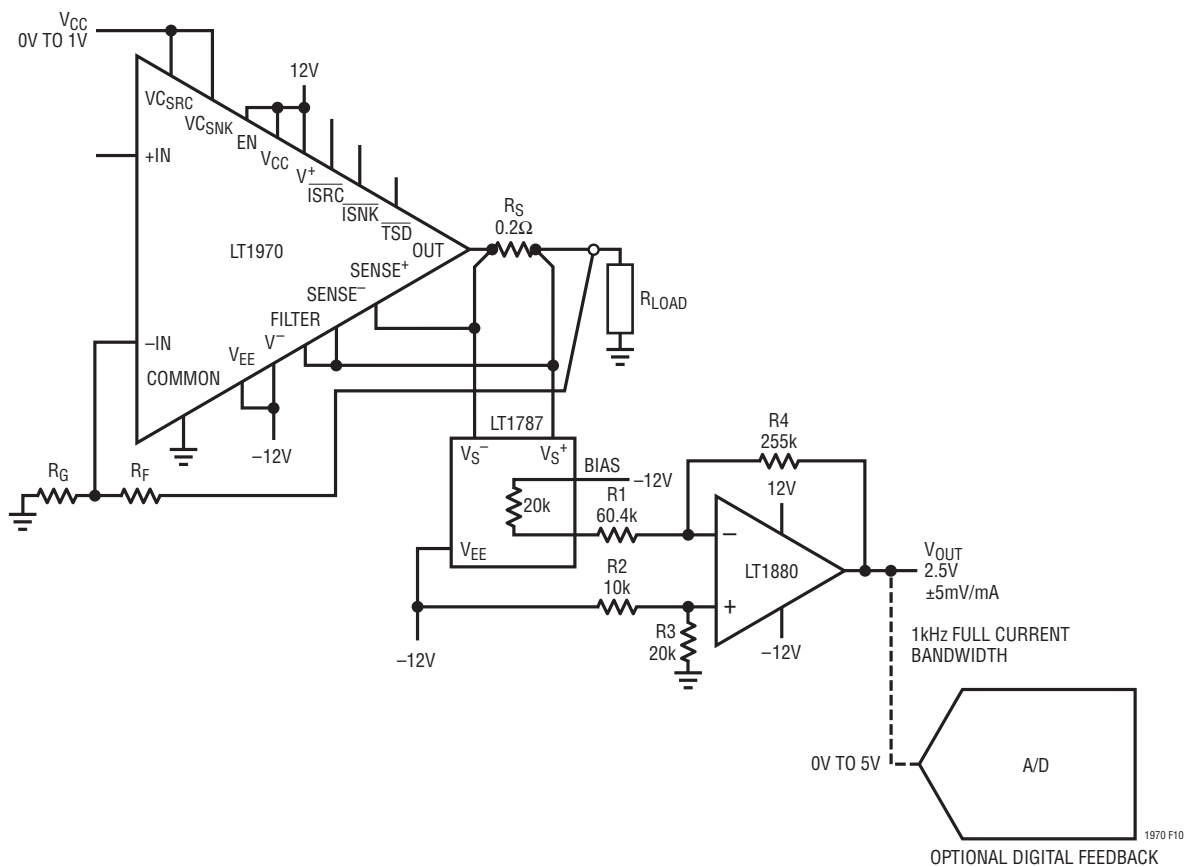

Figure 172. Sensing Output Current

DIGITIZING

Split or Single-Supply Operation, Bidirectional Output into A/D (Figure 173)

In this circuit, split supply operation is used on both the LT1787 and LT1404 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 midspan of the ADC input range.

16-Bit Resolution Unidirectional Output into LTC2433 ADC (Figure 174)

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.
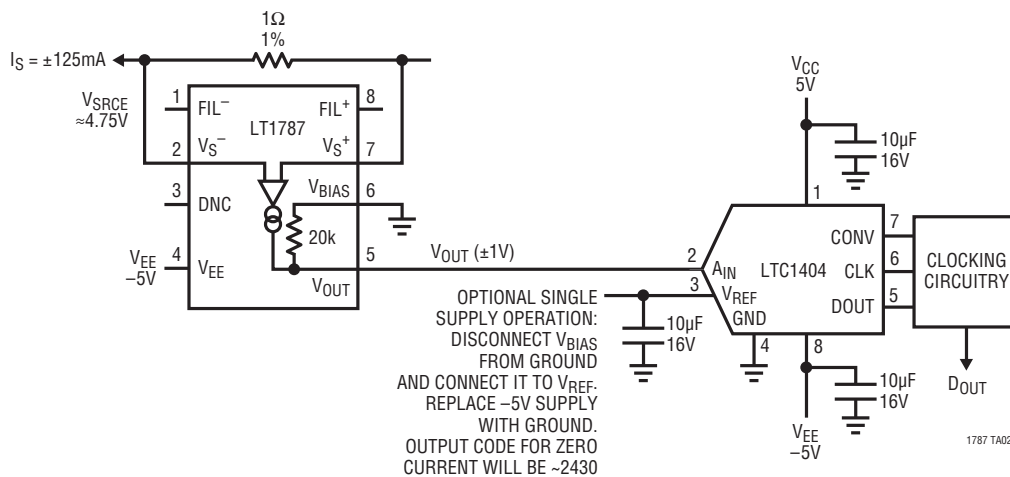

Figure 173. Split or Single-Supply Operation, Bidirectional Output into A/D
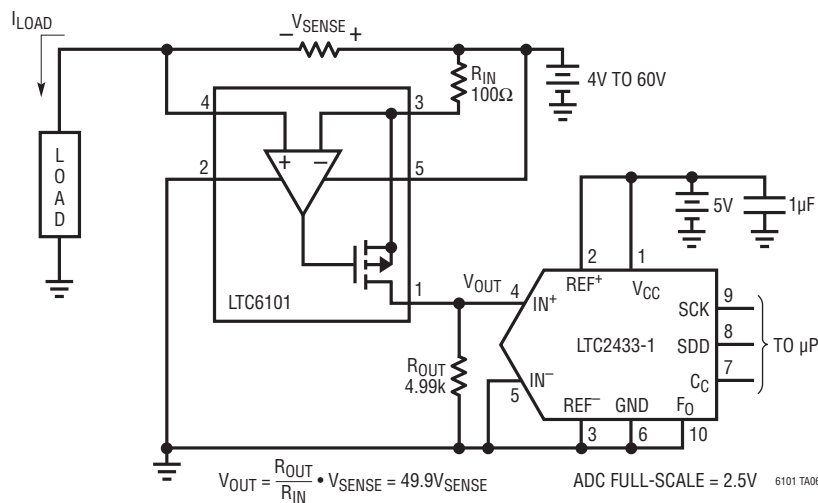

Figure 174. 16-Bit Resolution Unidirectional Output into LTC2433 ADC

DIGITIZING

12-Bit Resolution Unidirectional Output into LTC1286 ADC (Figure 175)

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.

Directly Digitize Current with 16-Bit Resolution (Figure 176)

The low offset precision of the LTC6102 permits direct digitization of a high side sensed current. The LTC2433 is a 16-bit delta sigma converter with a 2.5V full-scale range. A resolution of 16 bits has an LSB value of only 40µV. In this circuit the sense voltage is amplified by a factor of 50. This translates to a sensed voltage resolution of only 0.8µV per count. The LTC6102 DC offset typically contributes only four LSB's of uncertainty.
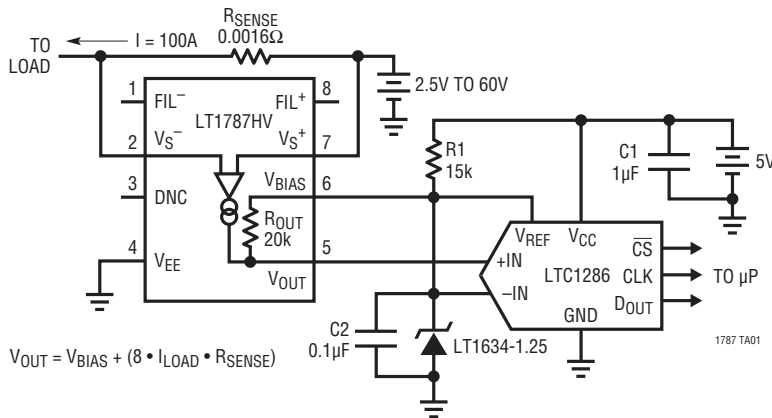

$$V_{OUT} = V_{BIAS} + (8 \cdot I_{LOAD} \cdot R_{SENSE})$$

Figure 175. 12-Bit Resolution Unidirectional Output into LTC1286 ADC

$$V_{OUT} = \frac{R_{OUT}}{R_{IN}} \cdot V_{SENSE} = 49.9 V_{SENSE}$$
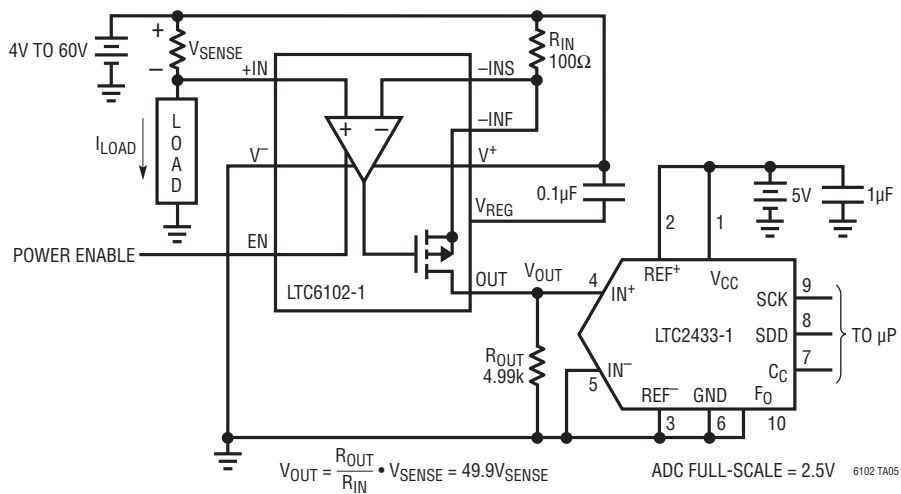
ADC FULL-SCALE = 2.5V

Figure 176. Directly Digitize Current with 16-Bit Resolution

DIGITIZING

Directly Digitizing Two Independent Currents (Figure 177)

With two independent current sense amplifiers in the LTC6103, two currents from different sources can be simultaneously digitized by a 2-channel 16-bit ADC such as the LTC2436-1. While shown to have the same gain on each channel, it is not necessary to do so. Two different current ranges can be gain scaled to match the same full-scale range for each ADC channel.

Digitize a Bidirectional Current Using a Single-Sense Amplifier and ADC (Figure 178)

The dual LTC6104 can be connected in a fashion to source or sink current at its output depending on the direction of current flow through the sense resistor. Biasing the amplifier output resistor and the V_{REF} input of the ADC to an external 2.5V LT1004 voltage reference allows a 2.5V full-scale input voltage to the ADC for current flowing in either direction.
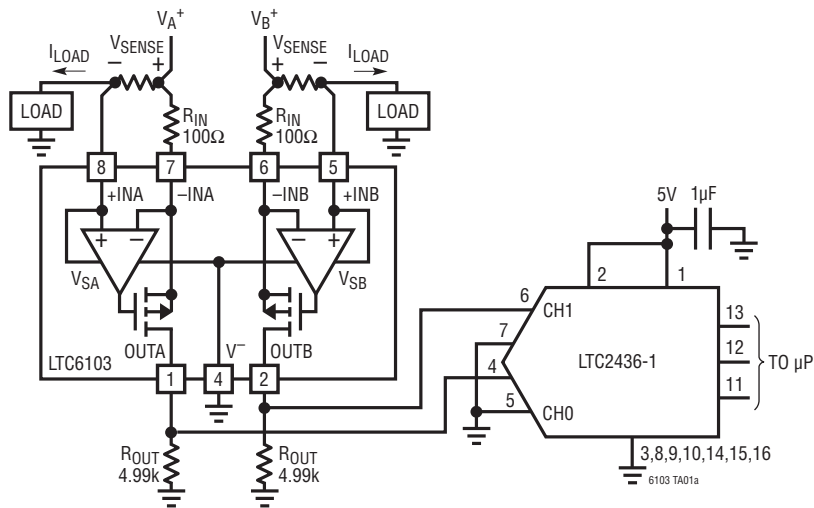

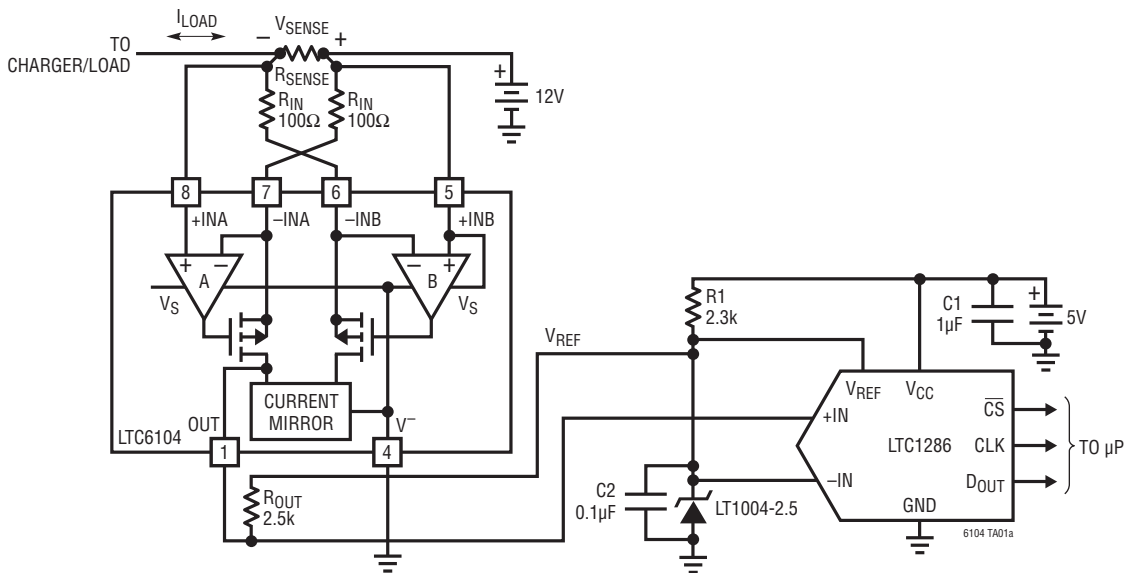Figure 177. Directly Digitizing Two Independent Currents

Figure 178. Digitize a Bidirectional Current Using a Single-Sense Amplifier and ADC

DIGITIZING

Digitizing Charging and Loading Current in a Battery Monitor (Figure 179)

A 16-bit digital output battery current monitor can be implemented with just a single sense resistor, an LT1999 and an LTC2344 delta sigma ADC. With a fixed gain of ten and DC biased output the digital code indicates the instantaneous loading or charging current (up to 10A) of a system battery power source.

Complete Digital Current Monitoring (Figure 180)

An LTC2470 16-bit delta sigma A-to-D converter can directly digitize the output of the LT6109 representing a circuit load current. At the same time the comparator outputs connect to MCU interrupt inputs to immediately signal programmable threshold over and undercurrent conditions.
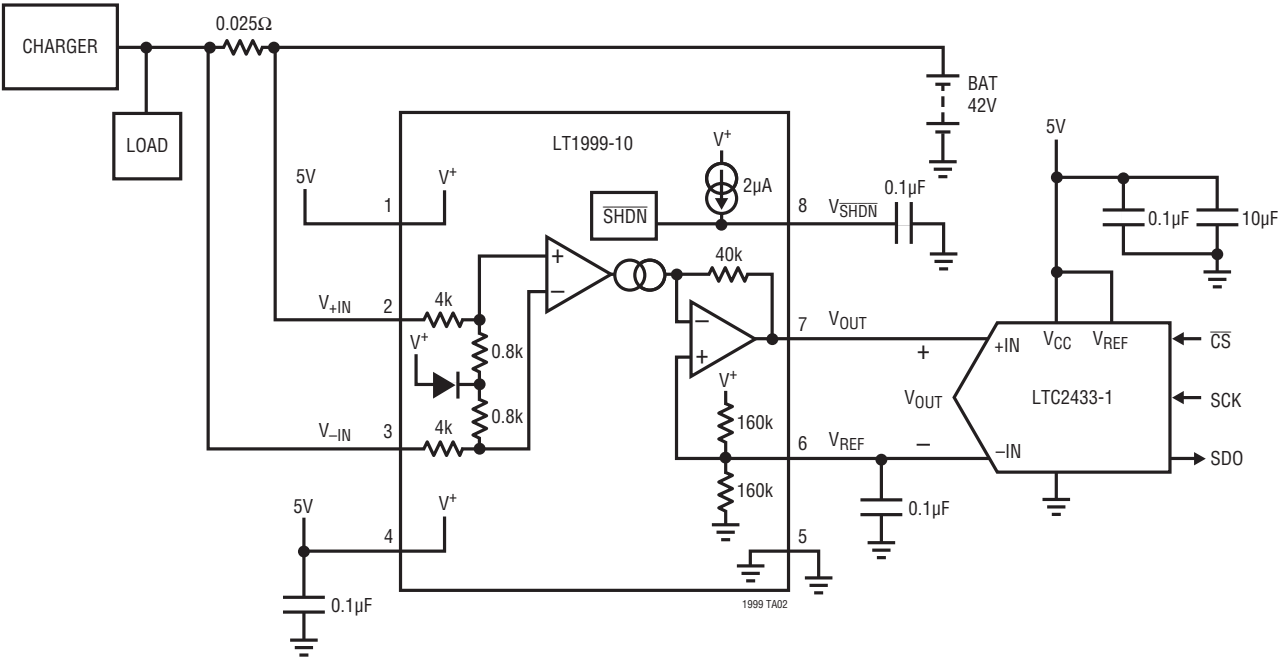

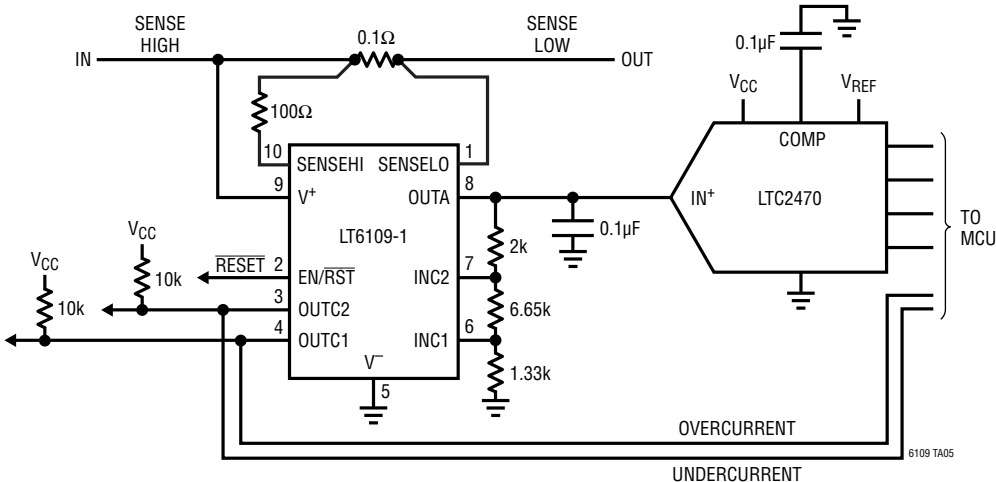**Figure 179. Digitizing Charging and Loading Current in a Battery Monitor**

Figure 180. Complete Digital Current Monitoring

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DIGITIZING

Ampere-Hour Gauge (Figure 181)

With specific scaling of the current sense resistor, the LTC4150 can be set to output exactly 10,000 interrupt pulses for one Amp-hr of charge drawn from a battery source. With such a base-10 round number of pulses a series of decade counters can be used to create a visual 5-digit display. This schematic is just the concept. The polarity output can be used to direct the interrupt pulses to either the count-up or count-down clock input to display total net charge.
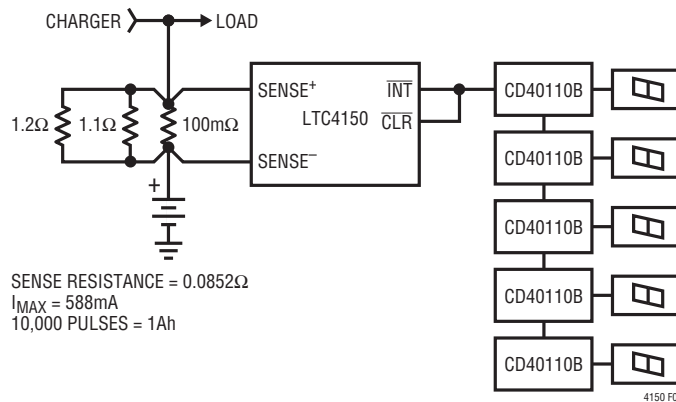
Power Sensing with Built-In A-to-D Converter (Figure 182)

The LTC4151 contains a dedicated current sense input channel to a 3-channel 12-bit delta-sigma ADC. The ADC directly and sequentially measures the supply voltage (102V full-scale), supply current (82mV full-scale) and a separate analog input channel (2V full-scale). The 12-bit resolution data for each measurement is output through an I^2C link.
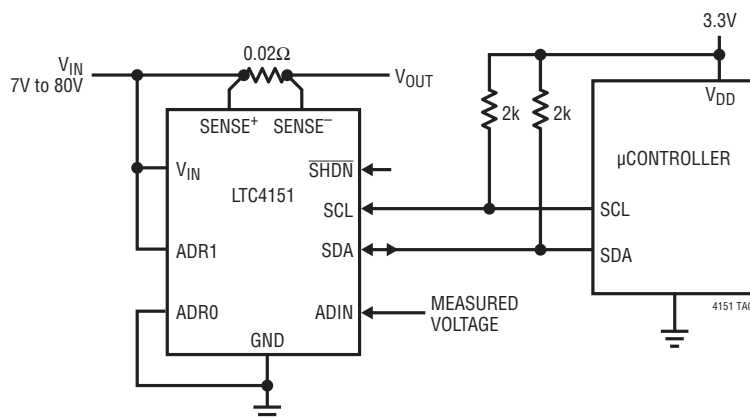

SENSE RESISTANCE = 0.0852Ω
I_{MAX} = 588mA
10,000 PULSES = 1Ah

Figure 181. Ampere-Hour Gauge

Figure 182. Power Sensing with Built-In A-to-D Converter

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DIGITIZING

Isolated Power Measurement (Figure 183)

With separate data input and output pins, it is a simple matter to fully isolate the LTC4151-1/LTC4151-2 from a controller system. The supply voltage and operating current of the isolated system is digitized and conveyed through three opto-isolators.

Fast Data Rate Isolated Power Measurement (Figure 184)

With separate data input and output pins, it is a simple matter to fully isolate the LTC4151-1/LTC4151-2 from a controller system. The supply voltage and operating current of the isolated system is digitized and conveyed through three high speed opto-isolators.
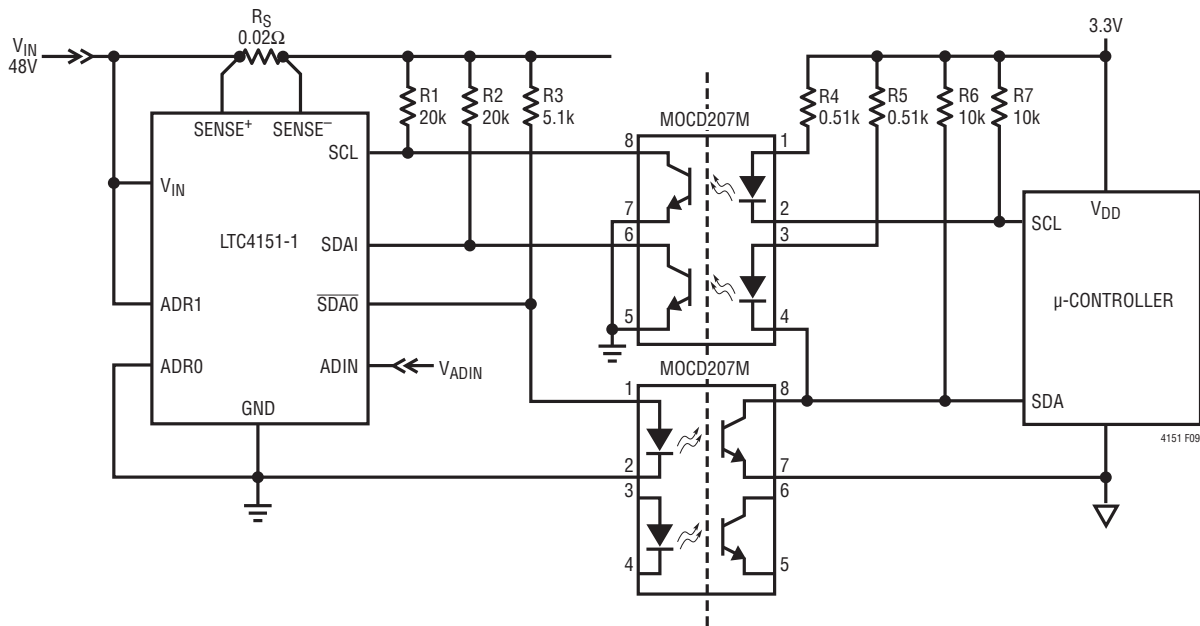

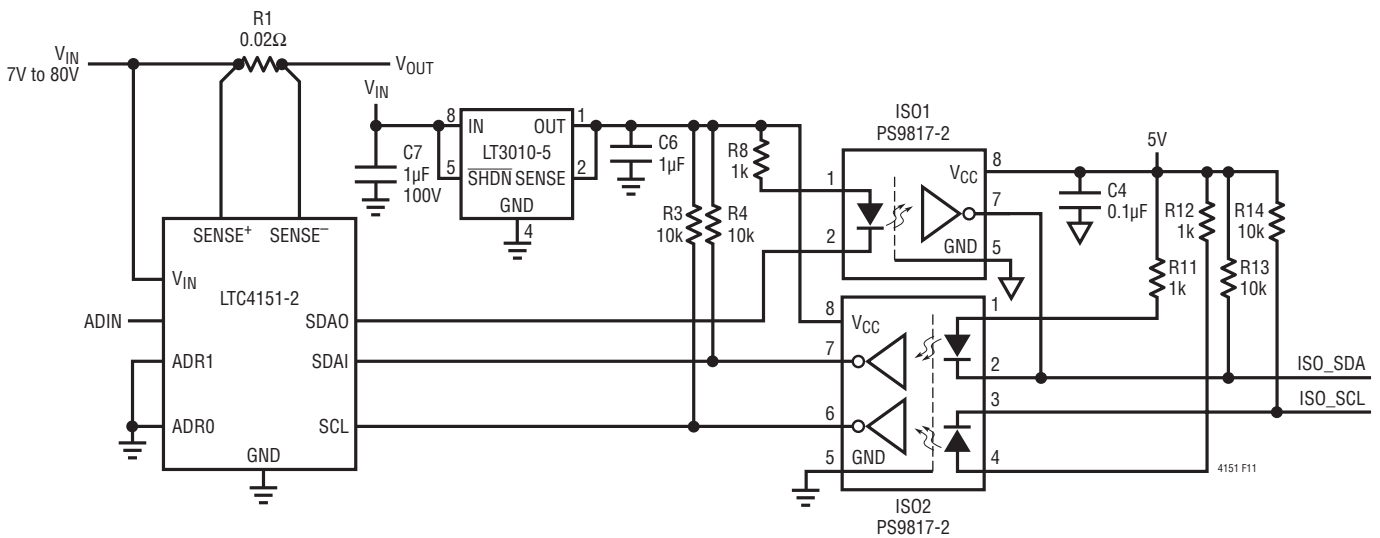**Figure 183. Isolated Power Measurement**

Figure 184. Fast Data Rate Isolated Power Measurement

DIGITIZING

Adding Temperature Measurement to Supply Power Measurement (Figure 185)

One use for the spare analog input of the LTC4151 could be to measure temperature. This can be done by using a thermistor to create a DC voltage proportional to temperature. The DC bias potential for the temperature network is the system power supply which is also measured, Temperature is derived from both measurements. In addition the system load current is also measured.

Current, Voltage and Fuse Monitoring (Figure 186)

Systems with redundant back-up power often have fuse protection on the supply output. The LTC4151, with some diodes and resistors can measure the total load current, supply voltage and detect the integrity of the supply fuses. The voltage on the spare analog input channel determines the state of the fuses.
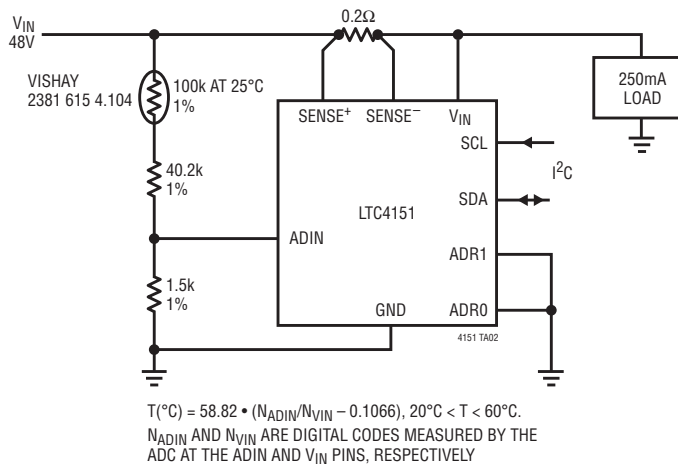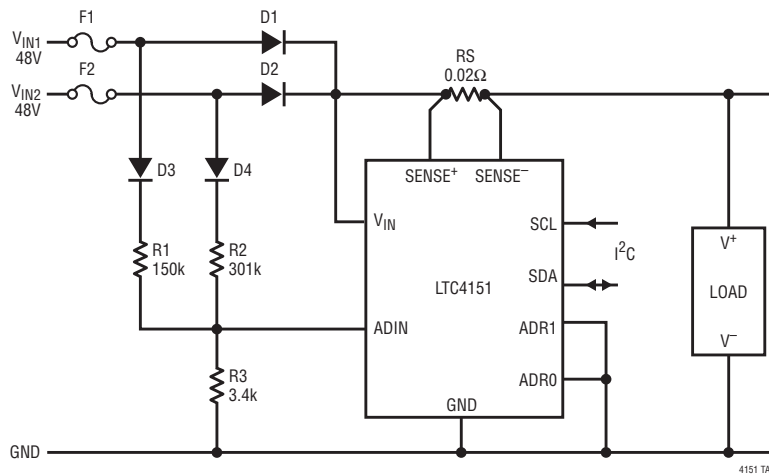

$T(°C) = 58.82 \cdot (N_{ADIN}/N_{VIN} - 0.1066)$, 20°C < T < 60°C.
N_{ADIN} AND N_{VIN} ARE DIGITAL CODES MEASURED BY THE ADC AT THE ADIN AND V_{IN} PINS, RESPECTIVELY

Figure 185. Adding Temperature Measurement to Supply Power Measurement

CONDITION	RESULT
$N_{ADIN} \geq 1.375 \cdot N_{VIN}$	Normal Operation
$0.835 \cdot N_{VIN} \leq N_{ADIN} < 1.375 \cdot N_{VIN}$	F2 is Open
$0.285 \cdot N_{VIN} \leq N_{ADIN} < 0.835 \cdot N_{VIN}$	F1 is Open
(Not Responding)	Both F1 and F2 are Open

V_{IN1} AND V_{IN2} ARE WITHIN 20% APART. N_{ADIN} AND N_{VIN} ARE DIGITAL CODES MEASURED BY THE ADC AT THE ADIN AND V_{IN} PINS, RESPECTIVELY.

Figure 186. Current, Voltage and Fuse Monitoring

DIGITIZING

Automotive Socket Power Monitoring (Figure 187)

The wide operating voltage range is adequate to permit the transients seen in automotive applications. The power consumption of anything plugged into an auto power socket can be directly digitized.

Power over Ethernet, PoE, Monitoring (Figure 188)

The power drawn by devices connected to an isolated telecom power supply can be continually monitored to ensure that they comply with their power class rating. A voltage proportional to the powered device rating is digitized by the spare analog input of the LTC4151-1.

Figure 187. Automotive Socket Power Monitoring

PD CLASS	V_{PWRMGT}
CLASS 1	0.237V
CLASS 2	0.417V
CLASS 3	0.918V

*R3 = 4 • 33k, 1/8W IN PARALLEL
**FASTER OPTOCOUPLERS PERMIT 100kHz OR 400kHz BUS OPERATIONS

Figure 188. Power over Ethernet, PoE, Monitoring

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DIGITIZING

Monitor Current, Voltage and Temperature
(Figure 189)

The LTC2990 is a 4-channel, 14-bit ADC fully configurable through an I^2C interface to measure single-ended, differential voltages and determine temperature from internal or external diode sensors. For high side current measurements two of the inputs are configured for differential input to measure the voltage across a sense resistor. The maximum differential input voltage is limited to ±300mV. Other channels can measure voltage and temperature for a complete system power monitor.
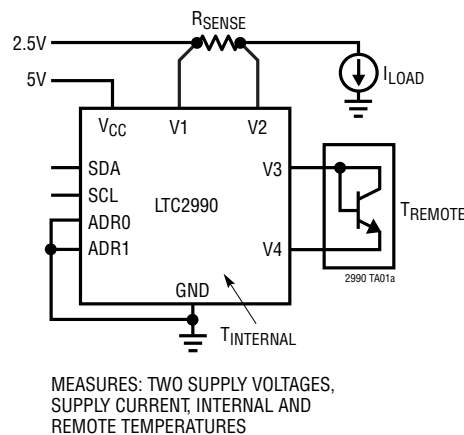

MEASURES: TWO SUPPLY VOLTAGES, SUPPLY CURRENT, INTERNAL AND REMOTE TEMPERATURES

Figure 189. Monitor Current, Voltage and Temperature

More Digitizing Circuits Are Shown in Other Chapters:

FIGURE	TITLE
20	Precision, Wide Dynamic Range High-side Current Sensing
93	High Voltage Current and Temperature Monitoring
130	Small Motor Protection and Control
131	Large Motor Protection and Control
148	Complete Single Cell Battery Protection
208	Remote Current Sensing with Minimal Wiring
210	Crystal/Reference Oven Controller
211	Power Intensive Circuit Board Monitoring
212	Crystal/Reference Oven Controller

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CURRENT CONTROL

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

800mA/1A White LED Current Regulator (Figure 190)

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 (Figure 191)

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.
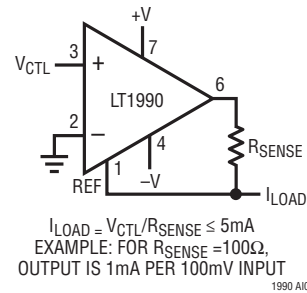

$I_{LOAD} = V_{CTL}/R_{SENSE} \le 5mA$
EXAMPLE: FOR $R_{SENSE} = 100\Omega$,
OUTPUT IS 1mA PER 100mV INPUT

Figure 191. Bidirectional Current Source

D1: DIODES INC.
D2: LUMILEDS LXML-PW09 WHITE EMITTER
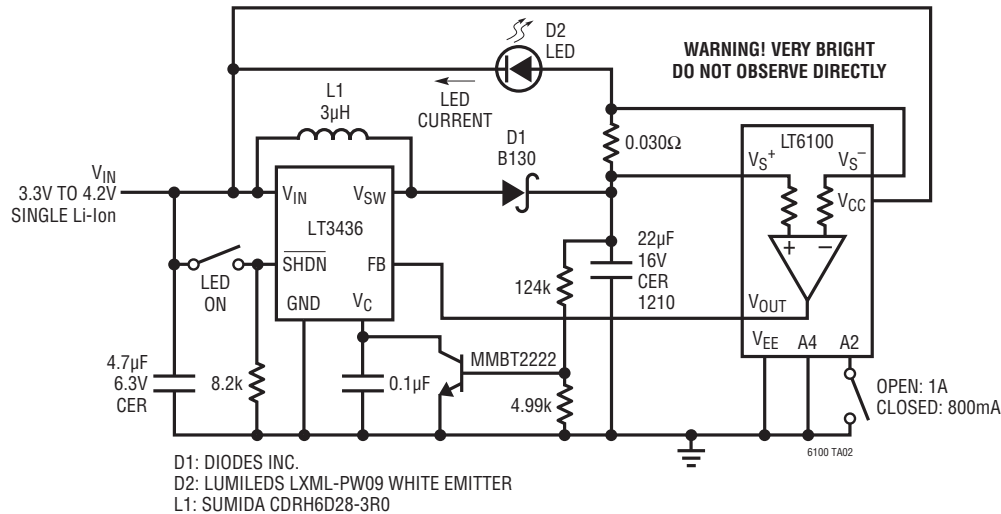L1: SUMIDA CDRH6D28-3R0

Figure 190. 800mA/1A White LED Current Regulator

CURRENT CONTROL

2-Terminal Current Regulator (Figure 192)

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.
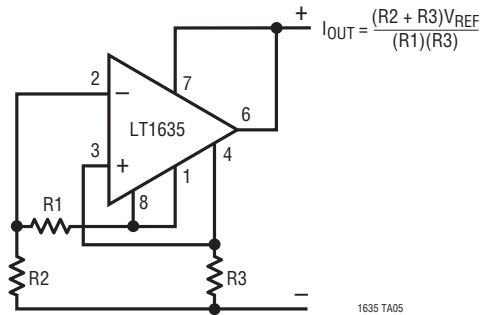
$$I_{OUT} = \frac{(R2 + R3)V_{REF}}{(R1)(R3)}$$

Figure 192. 2-Terminal Current Regulator

Variable Current Source (Figure 193)

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}.
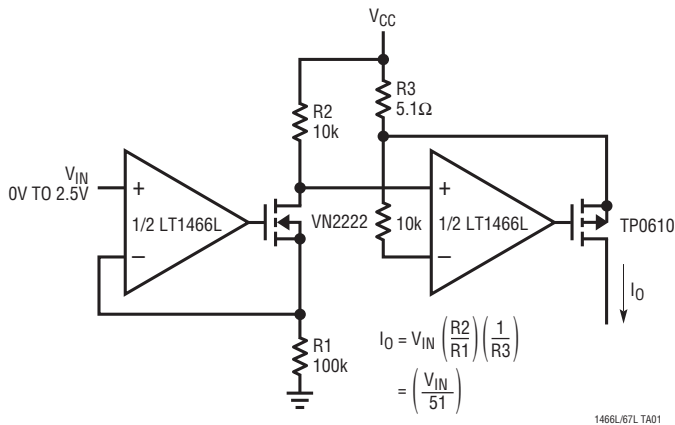
$$I_O = V_{IN}\left(\frac{R2}{R1}\right)\left(\frac{1}{R3}\right)$$

$$= \left(\frac{V_{IN}}{51}\right)$$

Figure 193. Variable Current Source

Precision Voltage Controlled Current Source with Ground Referred Input and Output (Figure 194)

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.
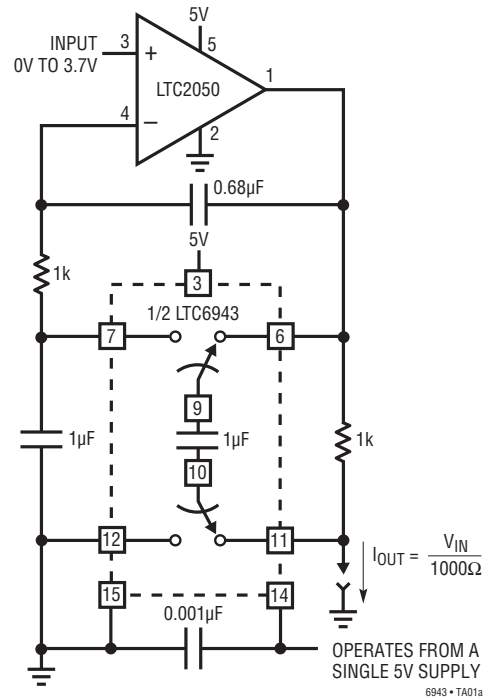
$$I_{OUT} = \frac{V_{IN}}{1000\Omega}$$

OPERATES FROM A
SINGLE 5V SUPPLY

Figure 194. Precision Voltage Controlled Current Source with Ground Referred Input and Output

an105fa

CURRENT CONTROL

Precision Voltage Controlled Current Source (Figure 195)

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.
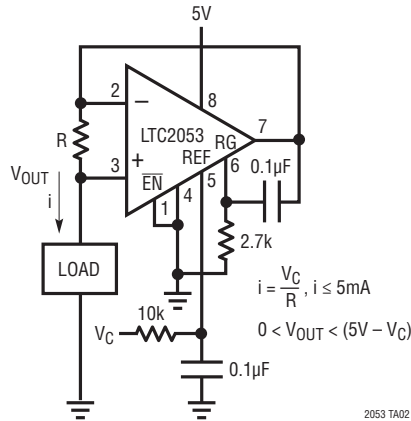

$$i = \frac{V_C}{R}, \, i \leq 5mA$$

$$0 < V_{OUT} < (5V - V_C)$$

Figure 195. Precision Voltage Controlled Current Source

Switchable Precision Current Source (Figure 196)

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.
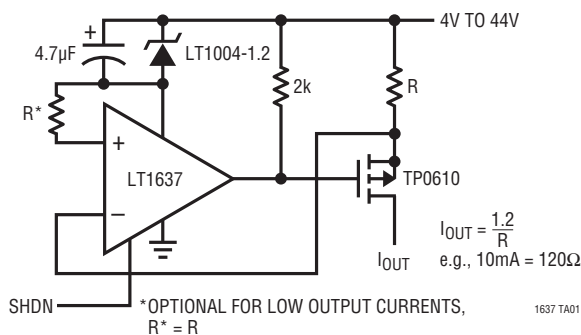

$$I_{OUT} = \frac{1.2}{R}$$

e.g., 10mA = 120Ω

*OPTIONAL FOR LOW OUTPUT CURRENTS,
R* = R

Figure 196. Switchable Precision Current Source

Boosted Bidirectional Controlled Current Source (Figure 197)

This is a classical Howland bidirectional current source implemented with an LT1990 integrated difference amplifier. The op amp circuit servos to match the R_{SENSE} voltage drop to the input command V_{CTL}. 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.
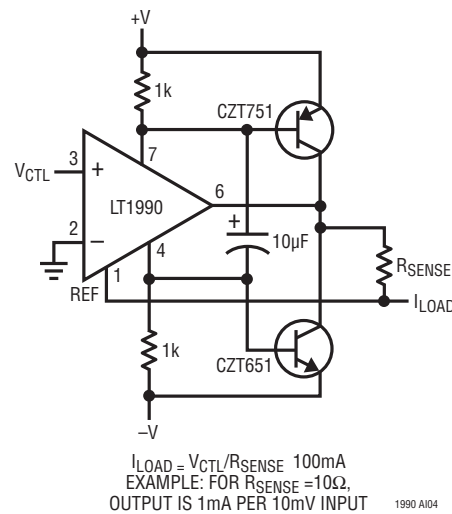

$I_{LOAD} = V_{CTL}/R_{SENSE}$ 100mA
EXAMPLE: FOR $R_{SENSE} = 10Ω$,
OUTPUT IS 1mA PER 10mV INPUT

Figure 197. Boosted Bidirectional Controlled Current Source

0A to 2A Current Source (Figure 198)

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 P-MOSFET as required to deliver the commanded current.
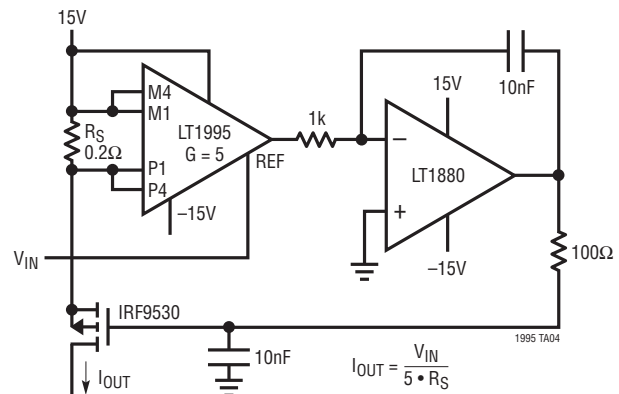

$$I_{OUT} = \frac{V_{IN}}{5 \cdot R_S}$$

Figure 198. 0A to 2A Current Source

CURRENT CONTROL

Fast Differential Current Source (Figure 199)

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.
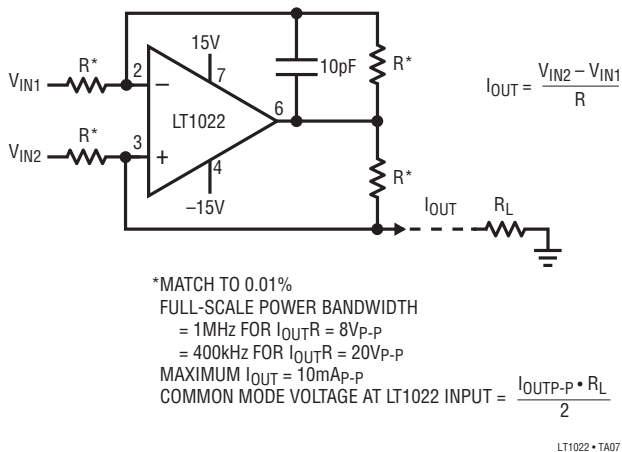

$$I_{OUT} = \frac{V_{IN2} - V_{IN1}}{R}$$

*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

Figure 199. Fast Differential Current Source

1A Voltage-Controlled Current Sink (Figure 200)

This is a simple controlled current sink, where the op amp drives the N-MOSFET 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.
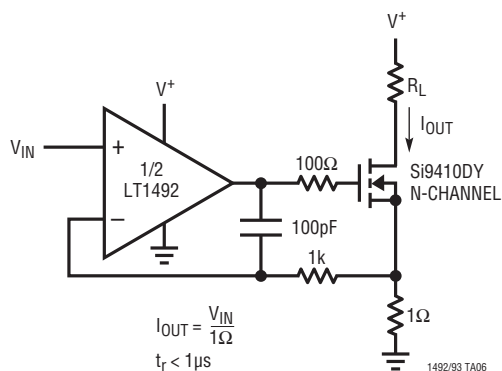

$$I_{OUT} = \frac{V_{IN}}{1\Omega}$$
$t_r < 1\mu s$

1492/93 TA06

Figure 200. 1A Voltage-Controlled Current Sink

Voltage Controlled Current Source (Figure 201)

Adding a current sense amplifier in the feedback loop of an adjustable low dropout voltage regulator creates a simple voltage controlled current source. The range of output current sourced by the circuit is set only by the current capability of the voltage regulator. The current sense amplifier senses the output current and feeds back a current to the summing junction of the regulator's error amplifier. The regulator will then source whatever current is necessary to maintain the internal reference voltage at the summing junction. For the circuit shown a 0V to 5V control input produces 500mA to 0mA of output current.
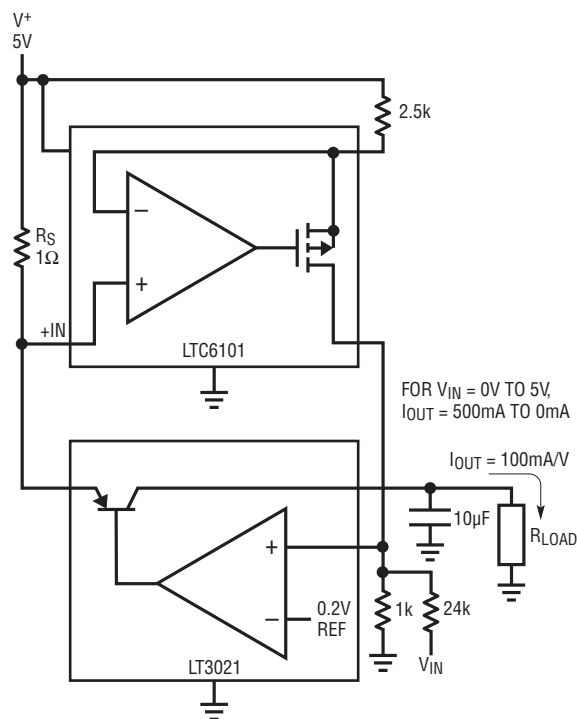

FOR V_{IN} = 0V TO 5V,
I_{OUT} = 500mA TO 0mA

I_{OUT} = 100mA/V

Figure 201. Voltage Controlled Current Source

LINEAR
TECHNOLOGY

CURRENT CONTROL

Adjustable High Side Current Source (Figure 202)

The wide-compliance current source shown takes advantage of the LT1366's ability to measure small signals near the positive supply rail. The LT1366 adjusts Q1's gate voltage to force the voltage across the sense resistor (R_{SENSE}) to equal the voltage between V_{DC} and the potentiometer's wiper. A rail-to-rail op amp is needed because the voltage across the sense resistor is nearly the same as V_{DC}. Q2 acts as a constant current sink to minimize error in the reference voltage when the supply voltage varies. At low input voltage, circuit operation is limited by the Q1 gate drive requirement. At high input voltage, circuit operation is limited by the LT1366's absolute maximum ratings.
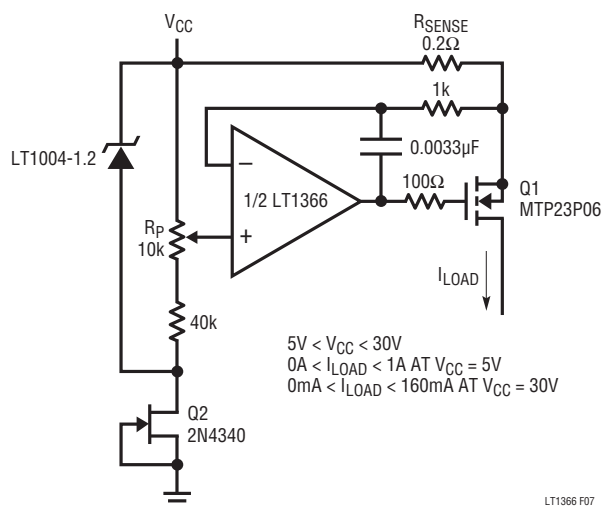

Figure 202. Adjustable High Side Current Source

Programmable Constant Current Source (Figure 203)

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 (Figure 204)

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.
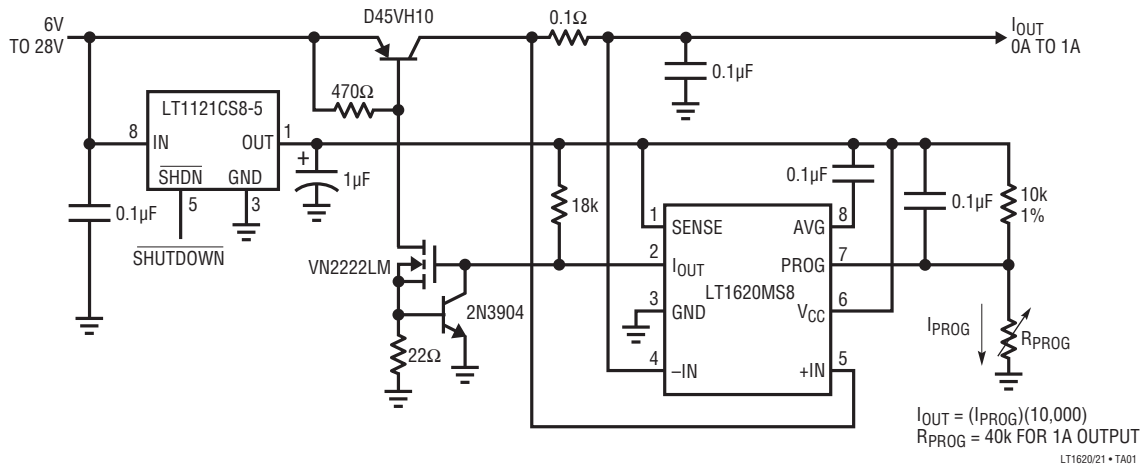
CURRENT CONTROL

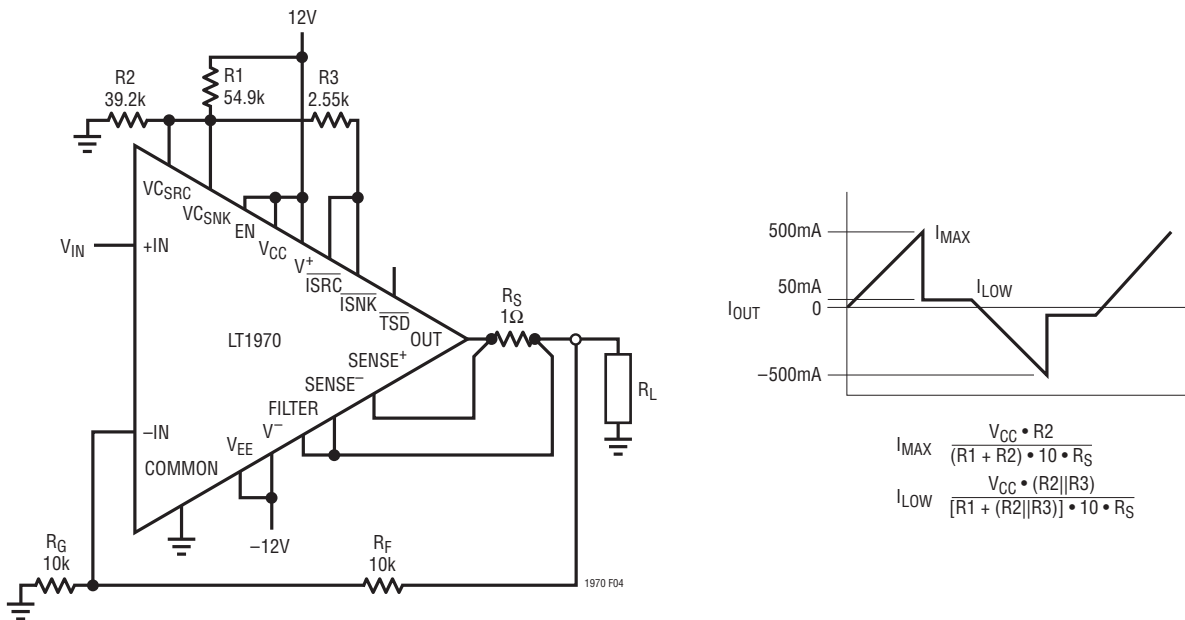Figure 203. Programmable Constant Current Source

Figure 204. Snap Back Current Limiting

More Current Control Circuits Are Shown in Other Chapters:

FIGURE	TITLE
120	Bidirectional Current Sensing in H-Bridge Drivers
129	Simple DC Motor Torque Control
170	Use Comparator Output to Initialize Interrupt Routines

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.

Precision High Side Power Supply Current Sense (Figure 205)

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.
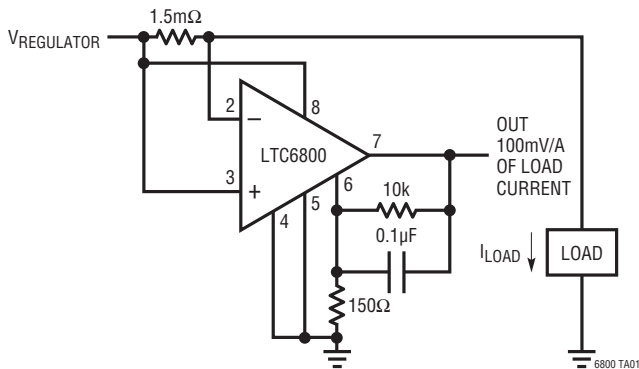

Figure 205. Precision High Side Power Supply Current Sense

High Side Power Supply Current Sense (Figure 206)

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 (Figure 207)

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.
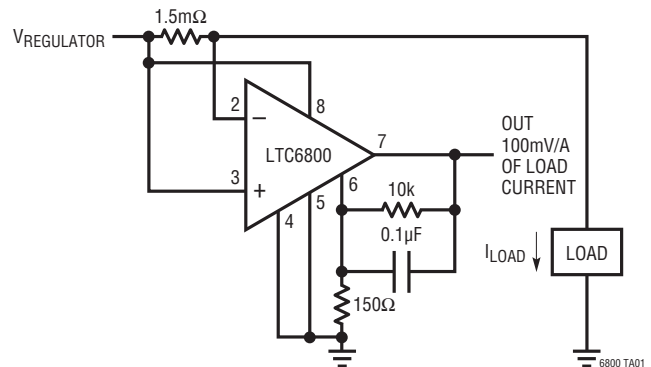

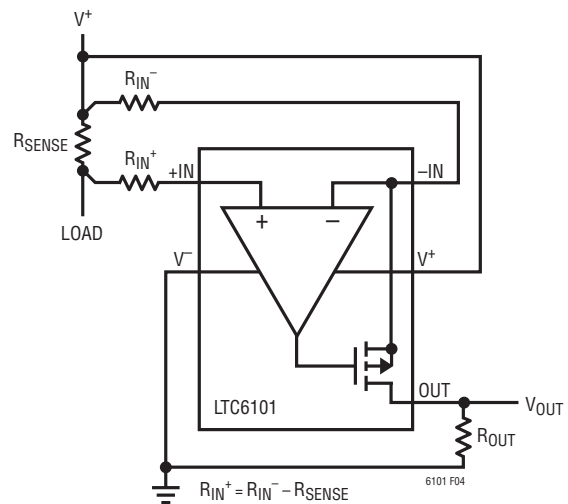Figure 206. High Side Power Supply Current Sense

Figure 207. Second Input R Minimizes Error Due to Input Bias Current

PRECISION

Remote Current Sensing with Minimal Wiring (Figure 208)

Since the LTC6102 (and others) has a current output that is ordinarily converted back to a voltage with a local load resistance, additional wire resistance and ground offsets don't directly affect the part behavior. Consequently, if the load resistance is placed at the far end of a wire, the voltage developed at the destination will be correct with respect to the destination ground potential.

Use Kelvin Connections to Maintain High Current Accuracy (Figure 209)

Significant errors are caused by high currents flowing through PCB traces in series with the connections to the sense amplifier. Using a sense resistor with integrated V_{IN} sense terminals provides the sense amplifier with only the voltage across the sense resistor. Using the LTC6104 maintains precision for currents flowing in both directions, ideal for battery charging applications.
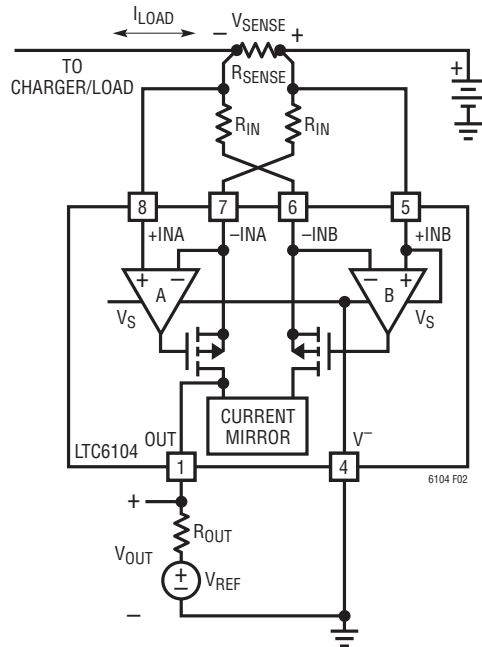

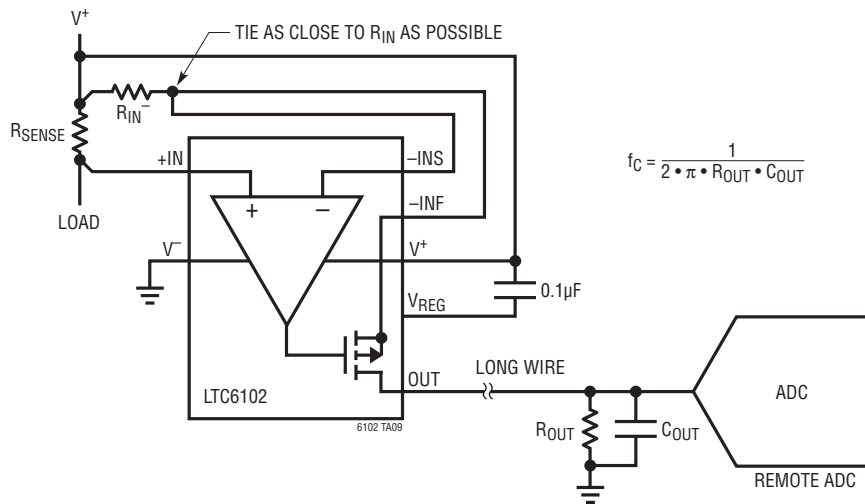Figure 209. Use Kelvin Connections to Maintain High Current Accuracy

$$f_C = \frac{1}{2 \cdot \pi \cdot R_{OUT} \cdot C_{OUT}}$$

Figure 208. Remote Current Sensing with Minimal Wiring

PRECISION

Crystal/Reference Oven Controller (Figure 210)

High precision instrumentation often use small ovens to establish constant operation temperature for critical oscillators and reference voltages. Monitoring the power (current and voltage) to the heater as well as the temperature is required in a closed-loop control system.

Power Intensive Circuit Board Monitoring (Figure 211)

Many systems contain densely populated circuit boards using high power dissipation devices such as FPGAs. 8-channel, 14-bit ADC LTC2991 can be used to monitor device power consumption with voltage and current measurements as well as temperatures at several points on the board and even inside devices which provide die temp monitoring. A PWM circuit is also built-in to provide closed-loop control of PCB operating temperature.
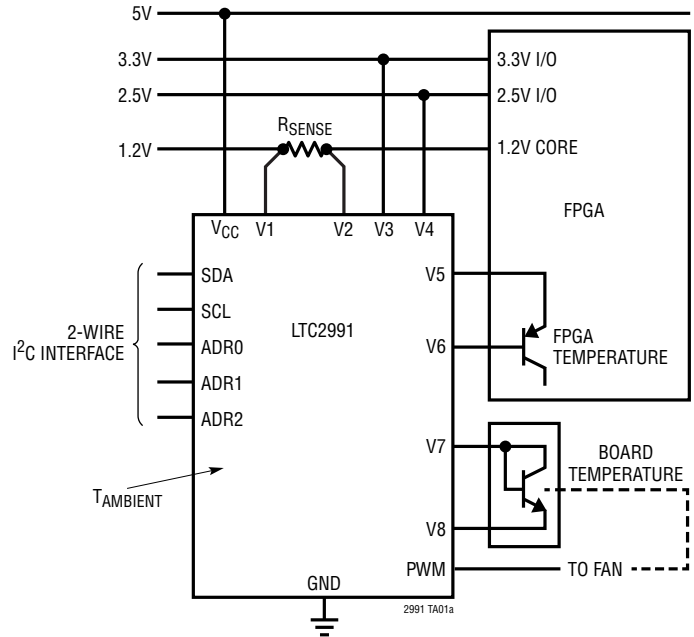

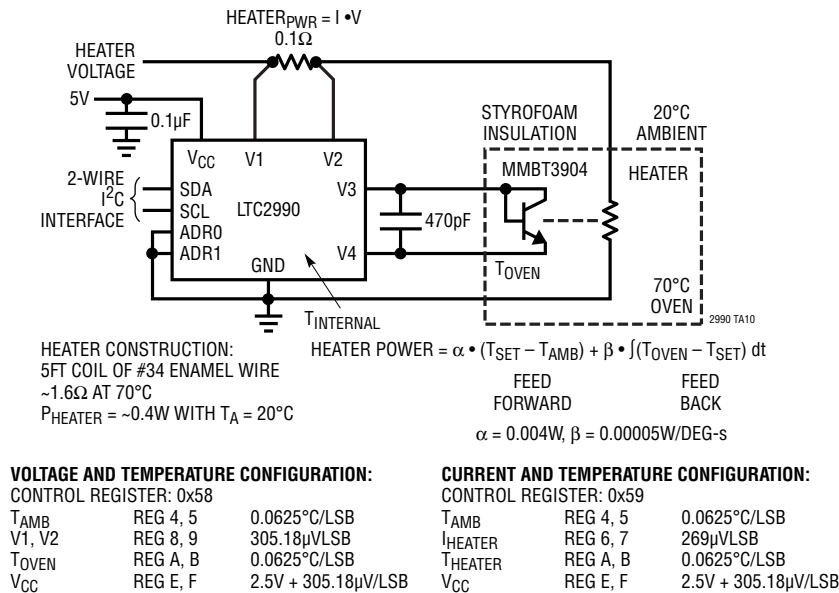**Figure 211. Power Intensive Circuit Board Monitoring**

HEATER CONSTRUCTION:
5FT COIL OF #34 ENAMEL WIRE
~1.6Ω AT 70°C
P_{HEATER} = ~0.4W WITH T_A = 20°C

HEATER POWER = $\alpha \cdot (T_{SET} - T_{AMB}) + \beta \cdot \int (T_{OVEN} - T_{SET})\, dt$

FEED
FORWARD

FEED
BACK

α = 0.004W, β = 0.00005W/DEG-s

VOLTAGE AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V1, V2	REG 8, 9	305.18µVLSB
T_{OVEN}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x59

T_{AMB}	REG 4, 5	0.0625°C/LSB
I_{HEATER}	REG 6, 7	269µVLSB
T_{HEATER}	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

Figure 210. Crystal/Reference Oven Controller

PRECISION

Crystal/Reference Oven Controller (Figure 212)

High precision instrumentation often use small ovens to establish constant operation temperature for critical oscillators and reference voltages. Monitoring the power (current and voltage) to the heater as well as the temperature is required in a closed-loop control system. The LTC2991 includes a PWM output which can provide closed-loop control of the heater.
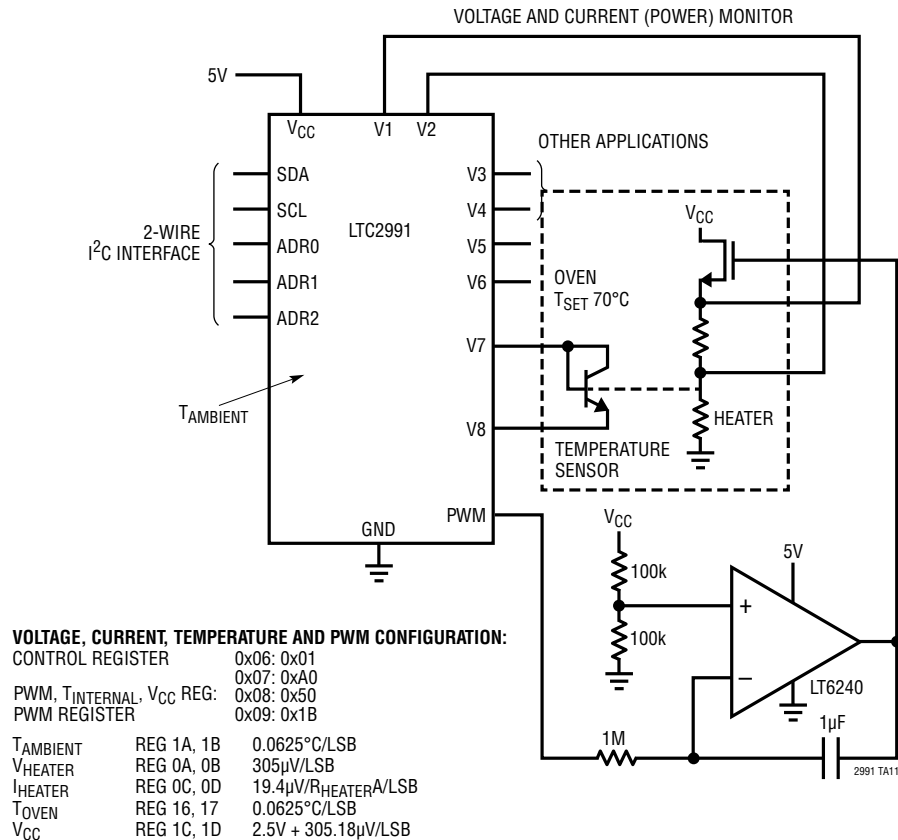

VOLTAGE, CURRENT, TEMPERATURE AND PWM CONFIGURATION:

CONTROL REGISTER	0x06:	0x01
	0x07:	0xA0
PWM, $T_{INTERNAL}$, V_{CC} REG:	0x08:	0x50
PWM REGISTER	0x09:	0x1B
$T_{AMBIENT}$	REG 1A, 1B	0.0625°C/LSB
V_{HEATER}	REG 0A, 0B	305µV/LSB
I_{HEATER}	REG 0C, 0D	19.4µV/R_{HEATER}A/LSB
T_{OVEN}	REG 16, 17	0.0625°C/LSB
V_{CC}	REG 1C, 1D	2.5V + 305.18µV/LSB

Figure 212. Crystal/Reference Oven Controller

PRECISION

More Precision Circuits Are Shown in Other Chapters:

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.

Dual LTC6101's Allow High-Low Current Ranging (Figure 213)

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

Adjust Gain Dynamically for Enhanced Range (Figure 214)

Instead of having fixed gains of 10, 12.5, 20, 25, 40, and 50, this circuit allows selecting between two gain settings. An N-MOSFET 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.
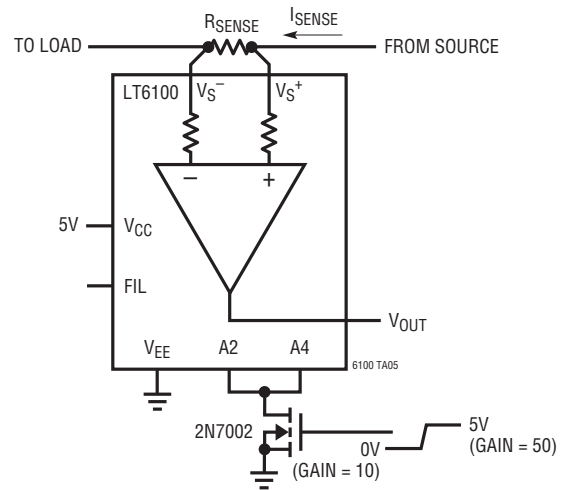

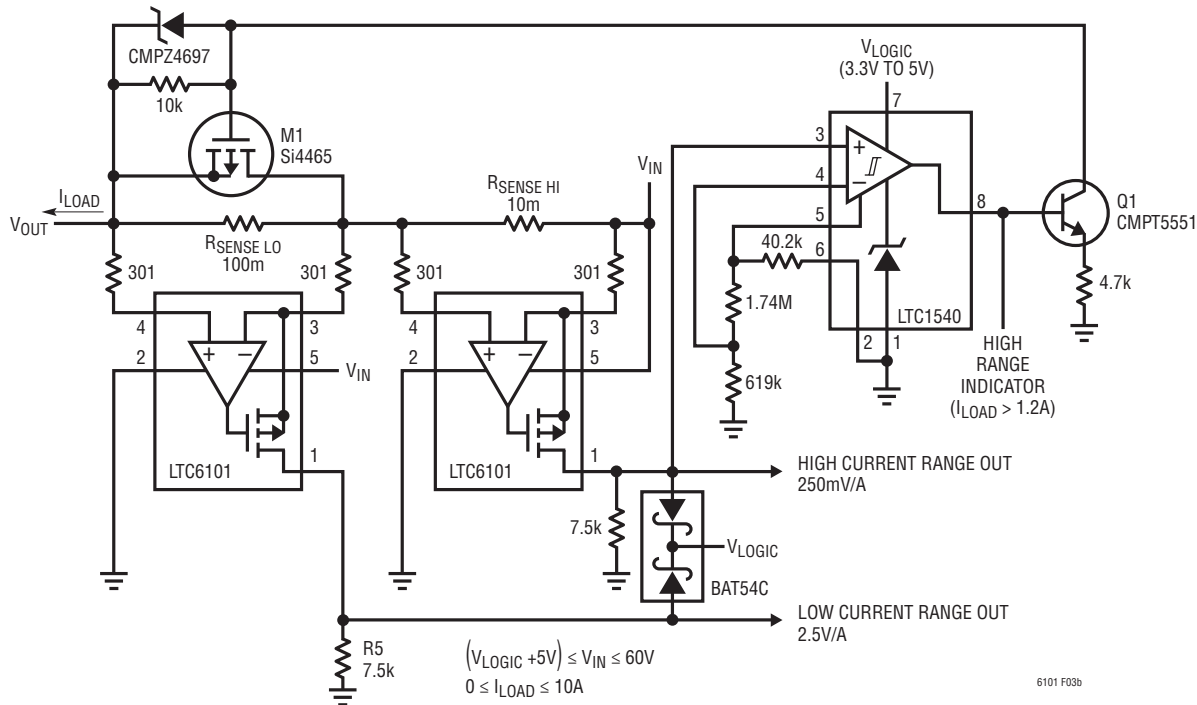**Figure 214. Adjust Gain Dynamically for Enhanced Range**

Figure 213. Dual LTC6101's Allow High-Low Current Ranging

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WIDE RANGE

0 to 10A Sensing Over Two Ranges (Figure 215)

Using two sense amplifiers a wide current range can be broken up into a high and low range for better accuracy at lower currents. Two different value sense resistors can be used in series with each monitored by one side of the LTC6103. The low current range, less than 1.2A in this example, uses a larger sense resistor value to develop a larger sense voltage. Current exceeding this range will create a large sense voltage, which may exceed the input differential voltage rating of a single sense amplifier. A comparator senses the high current range and shorts out the larger sense resistor. Now only the high range sense amplifier outputs a voltage.

Dual Sense Amplifier Can Have Different Sense Resistors and Gain (Figure 216)

The LTC6104 has a single output which both sources and sinks current from the two independent sense amplifiers. Different shunt sense resistors can monitor different current ranges, yet be scaled through gain settings to provide the same range of output current in each direction. This is ideal for battery charging application where the charging current has a much smaller range than the battery load current.
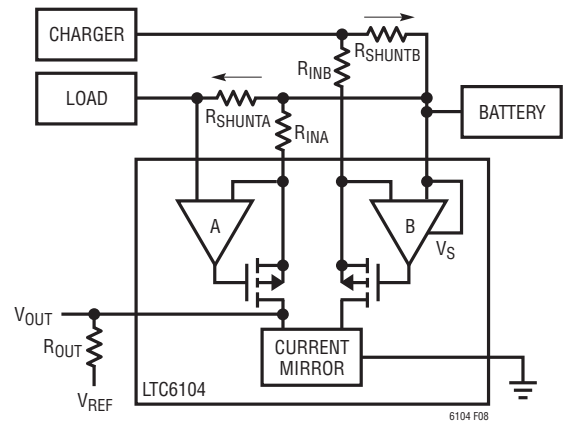

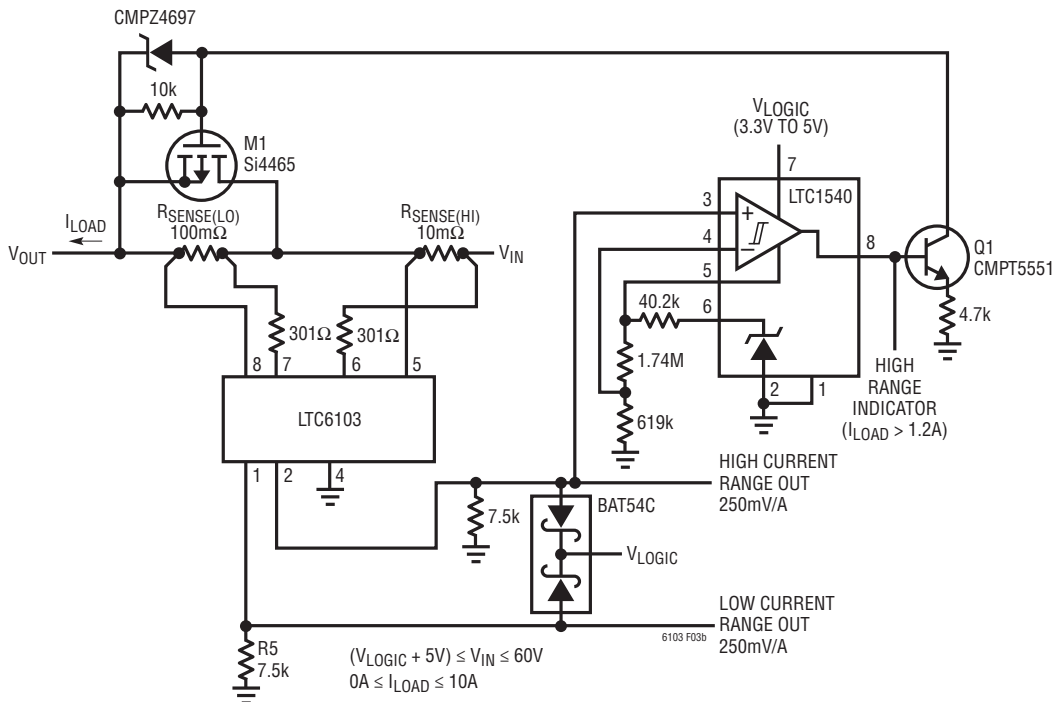**Figure 216. Dual Sense Amplifier Can Have Different Sense Resistors and Gain**

Figure 215. 0 to 10A Sensing Over Two Ranges

an105f

WIDE RANGE

More Wide Range Circuits Are Shown in Other Chapters: