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Finally, High Voltage Current Sensing Made Easy

by Brendan Whelan, Glen Brisebois, Albert Lee and Jon Munson

High Voltage Ability, Flexibility and Accuracy

The LT6100 and LTC6101 are high voltage precision high-side current sense amplifiers. Their simple architectures make them flexible and easy to use, while careful design has made them reliable and robust.

Key features include high supply range, user-configurable gains, low input current, high PSRR and low offset voltage. These features make the LT6100 and LTC6101 perfect for precision industrial and automotive sensing applications as well as current-overload protection circuits.

The LT6100 operates to 48V, is the simpler of the two to use, requiring almost no external components, draws little power, and is tolerant of several abnormal conditions such as split inputs, power off, and reverse battery.

The LTC6101 is the higher speed of the two, operates to 70V, and is more flexible, having external resistors set the gain. Both parts are available in a variety of small packages.

How Current Sensing Works

Current sensing is commonly accomplished in one of two ways. One method is magnetic, where a structure is created using permeable materials to couple an m-field to a coil or Hall-effect sensor. While non-intrusive to the measured circuit, a coil type pickup is intrinsically unable to provide any DC information (though exotic "flux-gate" techniques are possible), and Hall sensors generally lack the accuracy and sensitivity for most DC measurements.

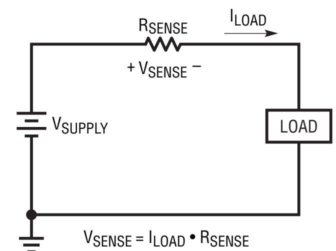

Figure 1. Typical high-side current-sense circuit

The alternative is the introduction of a known "sense" resistance in the load path, thereby creating a small voltage drop that is directly proportional to the load current. Generally, the preferred connection for a sense resistor is in the supply side of the circuit, so that common grounding practices can be retained and load faults can be detected. In the case of positive supply potentials, this connection is commonly referred to as a "high-side" sense configuration, as shown schematically in Figure 1. This means that the sense voltage is a small difference on a large common-mode signal from the perspective of the sense amplifier, which poses unusual demands on the implementation to preserve accuracy and dynamic range.

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LT6100 and LT6101, continued from page 1

Traditional grow-your-own solutions use operational or instrumentation amplifiers, but these are commonly limited in the voltage range of operation and/or require a number of additional components to perform the voltage translation function to create a ground-referenced readout signal. Far better and simpler solutions are attainable by using the LT6100 and LTC6101, which solve most high side current sensing requirements.

For an index of these and other current sense solutions, see Table 1. For specific applications where the current sensing is performed within dedicated chips or chip sets, see Table 2.

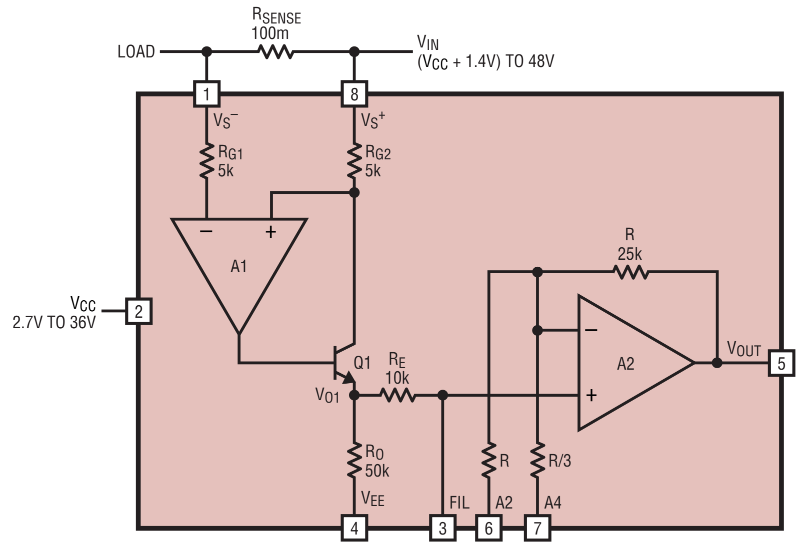


Figure 2. LT6100 simplified schematic

Watch Out for Sources of Current Sensing Error

As with any sensor design, there are several potential sources of error to consider. The accuracy of the circuit depends largely on how well the value of the sense resistor is known. The sense resistor itself has defined tolerances and temperature dependencies that introduce errors. Stray resistance in the measurement path or large dI/dt loops can also add errors. It is important to properly implement Kelvin connections to the sense resistor to minimize these effects.[1]

After sense resistance, the most significant source of error is the voltage offset of the sense amplifier, since it generates a level-independent uncertainty in the measurement. This is particularly important for preserving accuracy at current levels that are substantially below the maximum design value. In some applications it is desirable to calibrate out the static component of this term (in software, for example), but this may not always be practical.

An additional error source to consider is the tolerance of any resistors that may be required for setting scale factors. This can contribute to full-scale uncertainty along with the sense resistor and Kelvin connection tolerances. For the LT6100, scaling resistors are all provided on-chip, so the tolerances are well defined and accounted for in the data sheet specifications. In the case of the LTC6101, the scaling accuracy is set strictly by the user's choice of resistors, thereby allowing optimization for particular requirements.

LT6100 Theory of Operation

Figure 2 shows a simplified schematic of the LT6100 sensing across a 100mΩ sense resistor. The differential voltage across the sense resistor is imposed upon internal resistor R_{G2} by the action of the op amp A1 through Q1's collector. The resulting current through R_{G2} is thus $I = V_{SENSE}/R_{G2}$, and this current flows through Q1 and R_O. The voltage which appears across R_O is $R_O \bullet V_{SENSE}/RG2$. But R_O is ten times the value of R_{G2}, so the voltage is simply $10 \bullet V_{SENSE}$. This gives rise to the LT6100's inherent gain of 10 up to this point. The next stage involving op amp A2 gives the designer the flexibility of selecting further gain by grounding or floating pins A2 and A4 or connecting them to the output. Gains of 1, 1.25, 2, 2.5, 4, and 5 can be set here, for overall gains of 10, 12.5, 20, 25, 40, and 50. Series resistor R_E is provided between the two stages to allow simple low pass filtering by adding a capacitor at the FIL pin.

LTC6101 Theory of Operation

Figure 3 shows a simplified schematic of the LTC6101 in a basic current-sense circuit. As before, a sense resistor, R_{SENSE}, is added in series with the system supply at the positive (high side) of the supply. The internal amplifier of the LTC6101 acts as a voltage follower, driving its inverting

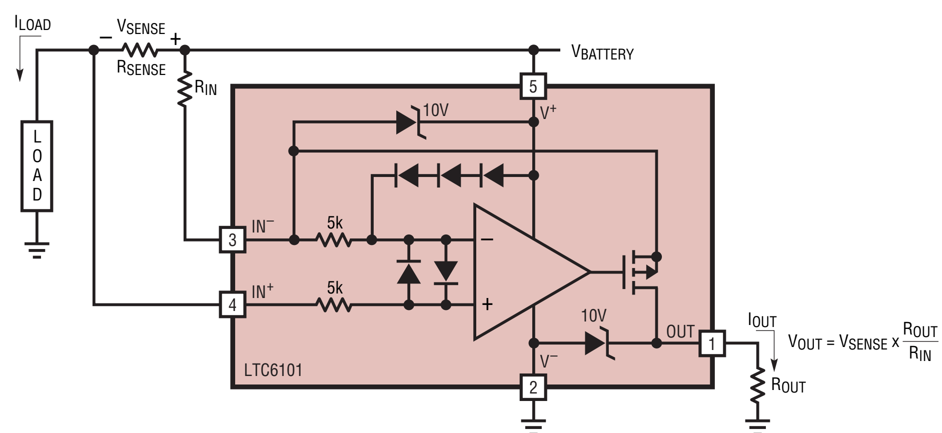


Figure 3. LTC6101 simplified schematic

[1] This topic is covered in depth in "Using Current Sensing Resistors with Hot Swap Controllers and Current Mode Voltage Regulators" in *Linear Technology* Magazine, September, 2003, pp. 34–35.

input (IN^-) to the same voltage as its non-inverting input (IN^+). This sets a voltage across R_{IN} that is equal to the voltage across R_{SENSE}:

$$V_{R(IN)} = V_{SENSE}$$

The current in R_{IN} is therefore:

$$I_{IN} = \frac{V_{SENSE}}{R_{IN}}$$

The amplifier inputs are high impedance, so this current does not flow into the amplifier. It is instead conducted through an internal MOSFET to the OUT pin, where it flows through R_{OUT} to ground. The output voltage is then:

$$V_{OUT} = I_{IN} \bullet R_{OUT},$$

and the gain is:

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

Substitute:

$$V_{SENSE} = R_{SENSE} \bullet I_{SENSE}$$

to yield the desired ratio of output voltage to sense current:

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

As with most current-sense solutions, the input and output voltages, as well as output current, are dictated by the application. In order to allow compatibility with most circuits, the LTC6101 supports input voltages between 0V and 500mV. This makes it suitable for most applications that use a small series sense resistor (or shunt). The LTC6101's output may be required to drive a comparator, ADC, or other circuitry. The output voltage can swing from 0V, since it is open-drain, to 8V. The output current may be set as high as 1mA, allowing useful speed and drive capability. The external gain resistors, R_{IN} and R_{OUT}, allow a wide range of gains to work in concert with these circuit constraints.

Table 1. Use this index of publications to find detailed applications information for current sensing solutions.

Publication	Hi Side/Low Side	Uni/Bi Directional	V_{OS} (CMRR)	Input Voltage/Feature
LT6100 Data Sheet	Hi Side	Uni	300	48V
LT6101 Data Sheet	Hi Side	Uni	300	60V
LT1787 Data Sheet	Hi Side	Bi	75µV	60V, 70µA
LT1990 Data Sheet, pp. 1, 16	Both	Bi	(80dB)	±250V
LT1991 Data Sheet, pp. 1, 19–22	Both	Bi	(80dB)	±60V
LT1995 Data Sheet, p. 20	Both	Bi		Hi Speed
LTC2054 Data Sheet, p. 12	Hi Side	Bi	3µV	60V
LTC2054 Data Sheet, p. 1	Low Side	Uni	3µV	–48V
LT1494 Data Sheet, p. 1, 16	Hi Side	Uni, Bi	~1mV	36V
LTC2053 Data Sheet, p. 13	Hi Side (Both possible)	Uni	10µV	5V
LTC6800 Data Sheet, p. 1	Hi Side (Both possible)	Uni	100µV	5V
LTC6943 Data Sheet p. 1	Both	Uni	(120dB)	18V
LT1620 Data Sheet	Both	Uni	5mV	36V, power
LT1366 Data Sheet, p.1	Hi Side	Uni	200µV	36V
LT1797 Data Sheet, p. 1	Low Side	Uni	1mV	–48V, fast
InfoCard 27				Various circuits
LT1637 Data Sheet, p. 13	Hi Side	Uni	~1mV	44V, Over-The-Top
LT1490A Data Sheet, p. 1	Hi Side	Bi	~1mV	12V, Over-The-Top
Design Note 341	Low Side	Uni	~1µV	–48V, Direct ADC
Linear Technology Magazine Aug. 2004, p. 33	Low Side	Bi	2.5µV	Direct ADC
Design Note 297	Hi Side	Uni	2.5µV	Direct ADC
LTC1966 Data Sheet, pp. 29, 32	Both (AC)			RMS Current
Application Note 92	Hi Side	Uni	various	Avalanche PDs

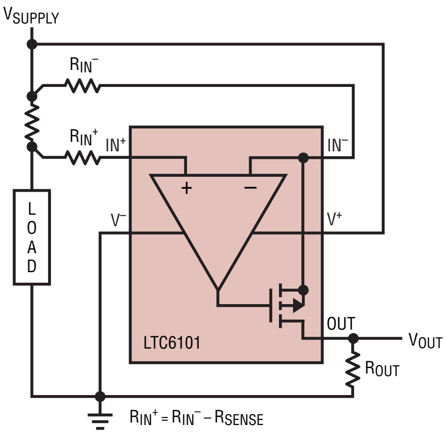


Figure 4. Second input resistor minimizes error due to input bias current

Input Precision: A Quick Comparison

Both the LT6100 and LTC6101 are very precise. They boast 300μV maximum input offset (500μV and 535μV, respectively, over temperature). Neither part draws supply current from the input sense pins. The LT6100 draws 5μA from its Over-The-Top® inputs, while the LTC6101 provides a separate supply pin (V+) to be connected to the sensed supply directly and draws only 100nA bias current at its inputs. This makes the LTC6101 ideal for very low current monitoring. In addition, the LTC6101 sense input currents are well matched so a second input resistor, R_{IN+} (Figure 4), may be added to cancel the effect of input bias. In this way the LTC6101 effective input bias error can be reduced to less than 15nA. The LT6100 provides these matched resistors internally, reducing its effective input bias current error to below 1μA.

Features

The LT6100: Robust and Easy to Use

The LT6100 tolerates a reverse battery on its inputs up to –50V, while guaranteeing less than 100μA of resultant fault current. In addition, it can also be used to sense across fuses and MOSFETs as shown in Figure 5. The LT6100 has no problem when the fuse or MOSFET opens because it has high voltage pnp's and a unique input topology that features full high impedance differential input swing capability to ±48V. This allows direct sensing of fuse or MOSFET voltage drops, without concern for the fuse or MOSFET open circuit condition.

Another unique benefit of the LT6100 is that you can leave it connected to a battery even when it is unpowered. When the LT6100 loses power, or is intentionally powered down, both sense inputs remain high impedance (see Figure 6). This is due to the implementation of Linear Technology's Over-The-Top input topology at the front end. In fact, when powered down, the LT6100 inputs actually draw less current than when powered up. Powered up or down, it represents a benign load.

The LTC6101: Delivers Accuracy and Speed in High Voltage Applications

The LTC6101 boasts a fully specified operating supply range of 4V to 60V, with a maximum supply voltage of 70V. Applications that require high operating voltages, such as motor control and telecom supply monitoring, or temporary high-voltage survival, such as with automotive load dump conditions, benefit from this wide supply range. The accuracy is preserved across this supply range by a high typical PSRR of 140dB.

The fast response time of the LTC6101 makes it suitable for overcurrent-protection circuits. The typical response time is less than 1μs for the output to rise 2.5V on a 5V output transition. The LTC6101 can detect a load fault and signal a comparator or microprocessor in time to open a switch in series with

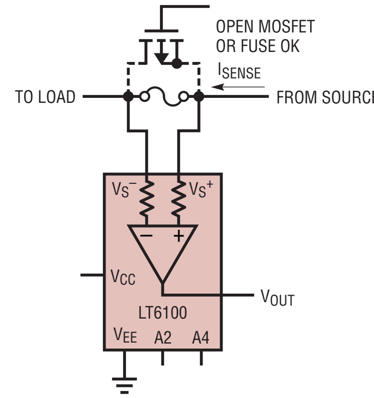


Figure 5. Sense across a MOSFET or fuse without worry. LT6100 inputs can split while remaining high Z.

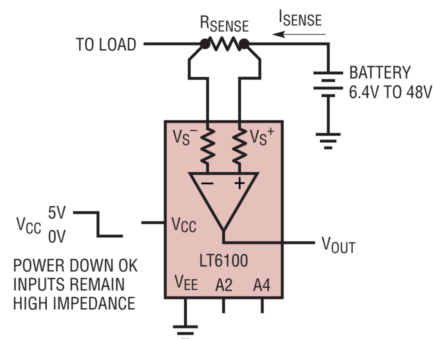
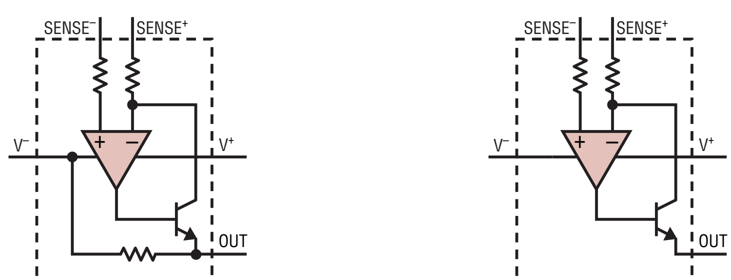


Figure 6. Remove power from the LT6100 with no need to disconnect the battery. The LT6100 inputs remain high Z.

the load before supply, load or switch damage occurs.

The architecture of the LTC6101 is the key to its flexibility. The gain is completely controlled by external resistors (R_{IN} and R_{OUT}, Figure 3). This is convenient because most applications specify a small maximum shunt voltage (to minimize power loss), which must be matched to either a specific comparator threshold or a desired ADC resolution. This requires that gain be



a. b.

Figure 7. The LT6101 achieves unparalled versatility in high side current sensing applications by allowing the user to select the gain via external R_{IN} and R_{OUT} resistors. In most architectures, some or all of these resistors are internal to the device, as shown here. Fixed gain devices, such as in (a), limit flexibility. Those with fixed input resistors, as in (b), limit gain and speed.

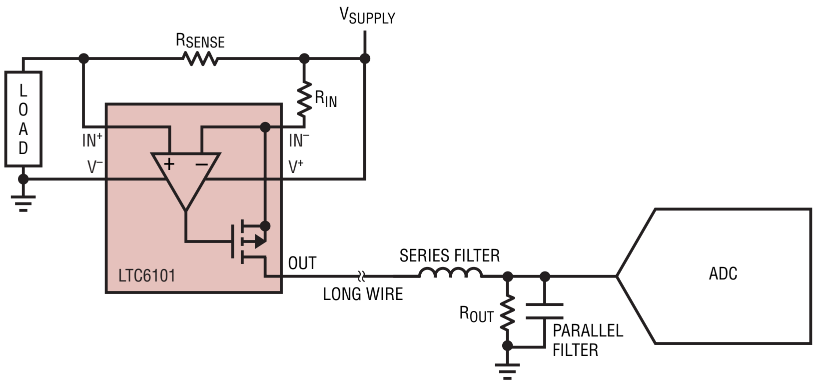


Figure 8. Open drain output enhances remote sensing accuracy.

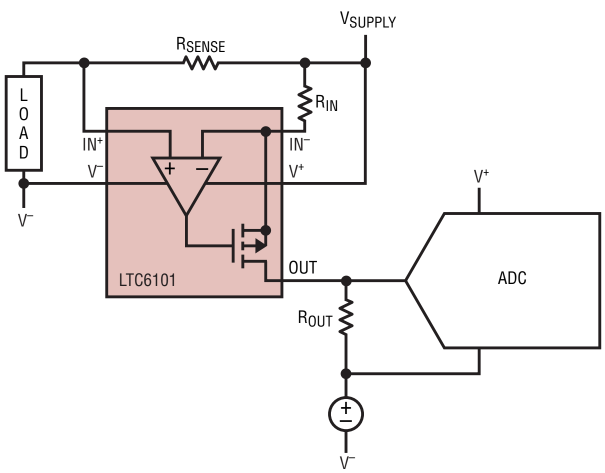


Figure 9. Output reference level shifted above V⁻

carefully set to maintain performance. In solutions where the gain resistors are not user-selectable (Figure 7a), the gain will be fixed, and may not be set to an appropriate value. Another approach is to include internal input resistors (Figure 7b), which allows user-configured gain, but may force the use of a very large output resistor in order to get high gain (10-100 or more). A large output resistor will cause the output to be slower and more susceptible to system noise, and may be too high an impedance to drive a desired ADC. The LTC6101 avoids these problems by allowing the application designer to choose both R_{IN} and R_{OUT}. R_{IN} can be quite small, its value limited only by the gain error due to stray board resistance and the 1mA maximum output current specification. Therefore high gain and high speed can be achieved even with small V_{SENSE} and R_{OUT} requirements. Gain accuracy is determined only by the accuracy of the external resistors.

In addition, the open-drain output architecture provides an advantage for remote-sensing applications. If the LTC6101 output must drive a circuit that is located remotely, such as an ADC, then the output resistor can be placed near the ADC. Since the open-drain output is a high-impedance current source, the resistive drop in the output wire will not affect the result at the converter. System noise that is coupled onto the long wire can be easily reduced with a series filter placed before R_{OUT}, or with a simple capacitor in parallel with R_{OUT}, with no loss of DC accuracy (Figure 8). The output may also be level shifted above V^- by terminating R_{OUT} at a voltage that is held higher than V^- (figure 9), provided that the maximum difference between V_{OUT} and V^- does not exceed the maximum specified output of the LTC6101.

Table 2. Linear Technology offers ICs for application-specific current-sensing solutions. Use this table to find publications that cover specific applications.

Publication	Application
LTC4060 Data Sheet	NiMH/NiCd charger
Linear Technology Magazine Mar. 2003, p. 24	Battery chargers
Linear Technology Magazine May 2004, p. 24	Battery gas gauge
Application Note 89	5V, TEC Controller
Application Note 66, Application Note 84	Switch Mode Power
LT Chronicle Jan. 2003, p. 7	Automotive Temp
Design Note 1009	Photo Flash
Design Note 312	VRM9.x
Design Note 347	Bricks
LTC4259, LTC4267 Data Sheet	Power over Ethernet
Design Solution 43	Altera FPGAs

Applications

Micro-Hotplate Current Monitor

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

While the exact methods of detection are highly complex and relatively proprietary, the method of creating localized heat is as old as the light bulb. Figure 10 shows 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.

White LED Current Controller

Figure 11 shows the LT6100 used in conjunction with the LT3436 switch mode power converter to efficiently drive a white LED with a constant current. By closing the switch on pin A2 of the LT6100, its gain is adjusted between 40 (open) and 50 (closed).

The FB pin of the LT3436 is a control pin referenced to a 1.2V set point. When the FB pin is above 1.2V, the LT3436 stops operation; when below 1.2V, the LT3436 continues operation. The output voltage (>1.2V) is usually regulated by applying a resistive divider from the output voltage back to the FB pin to close the feedback loop. To achieve a constant output current, rather than a constant output voltage, the feedback loop must convert the load current to a voltage. Enter the LT6100.

It senses the LED current by measuring the voltage across a 30mΩ resistor, applies a gain, and feeds the resulting voltage back to the FB pin.

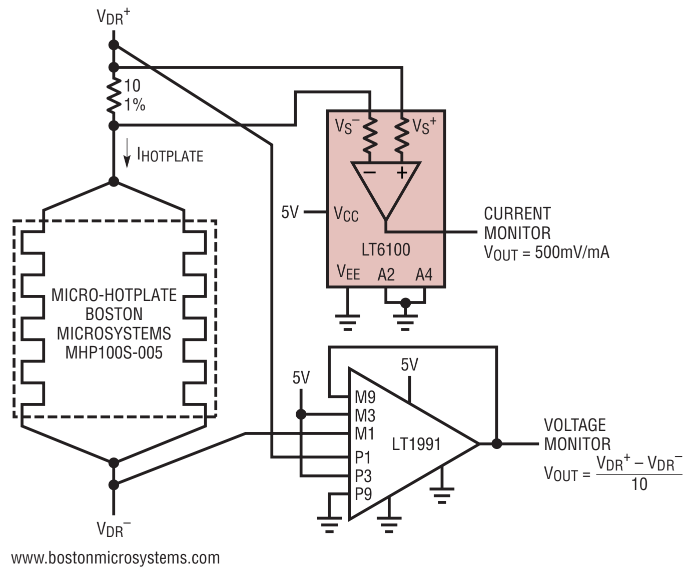


Figure 10. LT6100 and LT1991 monitor the current and voltage through a wide range of drive levels applied to a Microhotplate.

The 1.2V set point at the LT3436 can be referred back across the sense resistor by dividing by the LT6100 gains of 40 and 50. This gives 30mV and 24mV respectively. Dividing by the

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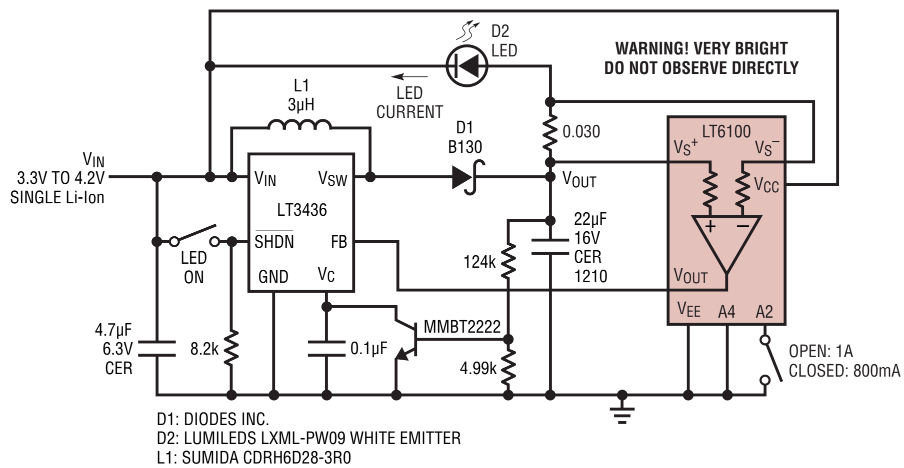

Figure 11. 1Amp/800mA white LED current controller

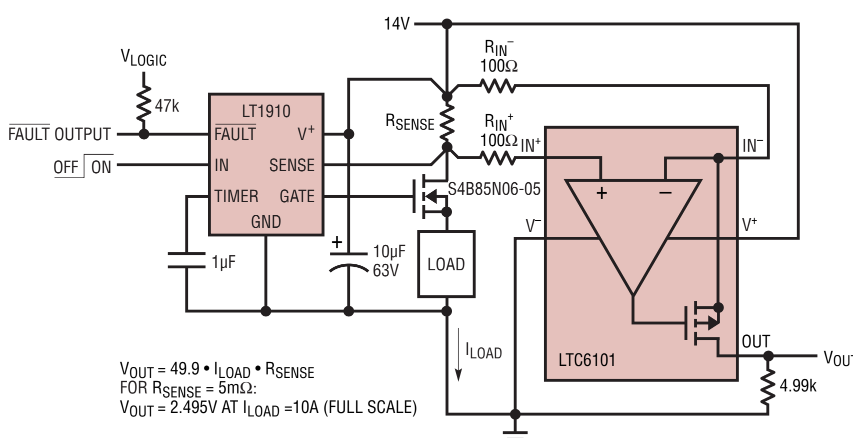

Figure 12. Automotive smart-switch with current readout

battery voltage rises with its charge (resulting in lower power dissipation across the MOSFET) but it is the worst case situation that one must account for when determining the maximum allowable values for charge current and IC temperature.

Once the die temperature drops below 115 °C, the LTC4059 returns to constant-current mode straight from constant temperature mode. As the battery voltage approaches the 4.2V float voltage, the part enters constant-voltage mode. In constant-voltage mode LTC4059 begins to decrease the charge current to maintain a constant voltage at the BAT pin rather than a constant current out of the BAT pin (Figure 3).

Regardless of the mode, the voltage at the PROG pin is proportional to the current delivered to the battery. During the constant current mode, the PROG pin voltage is always 1.21V indicating that the programmed charge current is flowing out of the BAT pin. In constant temperature mode or constant voltage mode, the BAT pin current is reduced. The charge current at any given charge cycle can be determined by measuring the PROG pin voltage using the formula I_{CHRG} = 1000 • (1.21V/R_{PROG}).

Using the battery voltage and the PROG pin voltage information, the user can determine the proper charge termination current level (typically 10% of the full-scale programmed charge current). Once the desired charge current level is reached, the user can terminate the charge cycle simply by pulling up the EN pin above 1.2V.

Board Layout

Properly soldering the exposed metal on the backside of the LTC4059 package is critical for minimizing the thermal resistance. Properly soldered LTC4059 on a 2500mm^2 double sided 1oz copper board should have a thermal resistance of approximately 60°C/W. When the LTC4059 is not properly soldered (or does not have enough copper), the thermal resistance rises, causing the LTC4059 to enter constant-temperature mode more often, thus resulting in longer charge time. As an example, a correctly soldered LTC4059 can deliver over 900mA to a battery from a 5V supply at room temperature. Without a backside thermal connection, this number could drop to less than 500mA.

Li$\overline{CC}$, $\overline{ACPR}$

Two versions of the part are available, depending on the needs of the battery chemistry. The LTC4059 has a Li$\overline{CC}$ pin, which disables constant-voltage operation when it is pulled up above 0.92V. In this mode, the LTC4059 turns into a precision current source capable of charging Nickel chemistry batteries. In the LTC4059A, the Li$\overline{CC}$ pin is replaced by an $\overline{ACPR}$ pin, which monitors the status of the input voltage with an open-drain output. When V_{cc} is greater than 3V and 150mV above the BAT pin voltage, the $\overline{ACPR}$ pin will pull to ground; other wise the pin is forced to a high impedance state.

Combining Wall Adapter and USB Power

Figure 4 shows an example of combining wall adapter and USB power inputs. In this circuit, MP1 is used to prevent back conduction into the USB port when a wall adapter is present and D1 is used to prevent USB power loss through the 1K pull-down resistor. The 2.43k resistor sets the charge current to 500mA when the USB port is used as input and the MN1 and 3.4k resistor is used to increase the charge current to 850mA when the wall adapter is present.

Conclusion

The LTC4059 is industry's smallest single cell Li-Ion battery charger capable of up to 900mA charge current. The thermal regulation feature of LTC4059 allows the designer to maximize the charge current and shorten the charge time without the risk of damaging the circuit. The small circuit size, thermal protection, low supply current and low external component count make LTC4059 an ideal solution for small portable and USB devices.

LT6100, LTC6101, continued from page 7

sense resistor of 30mΩ gives set point currents of 1A and 800mA.

Monitor the Current of Automotive Load Switches

With its 60V input rating, the LTC6101 is ideally suited for directly monitoring currents on vehicular power systems, without need for additional supply conditioning or surge protection components.

Figure 12 shows an LT1910-based intelligent automotive high-side switch with an LTC6101 providing an analog current indication. The LT1910 high-side switch controls an N-channel MOSFET that drives a controlled load, and uses a sense resistance to provide overload detection (note the surge-current of lamp filaments may cause a protection trip, thus are not recommended loads with the LT1910). The sense resistor is shared by the LT6101 to provide the current measurement.

The LTC6101 supplies a current output, rather than a voltage output, in proportion to the sense resistor voltage drop. The load resistor for the LTC6101 may be located at the far end of an arbitrary length connection, thereby preserving accuracy even in the presence of ground-loop voltages.

Conclusion

The LT6100 and LTC6101 are precise high side current sensing solutions. Although very similar in obvious respects, each has its unique advantages. The LT6100 draws much less power, can be powered down while maintaining high Z characteristics, and has nearly indestructible inputs. The LTC6101 can withstand up to 70V, is infinitely gain configurable, and provides an open drain output.