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## SiGe Differential Amplifier Drives High Speed ADCs at Hundreds of MHz

by Kris Lokere and Adam Shou

### Introduction

The last few years have seen great advances in the performance of analog-to-digital converters. Sampling rates for 12-, 14- and even 16-bit ADCs are now well above 100MSPs. The LTC<sup>®</sup>6400 differential amplifier has been specifically designed to drive these high performance ADC inputs in a way that maintains their excellent low noise and high linearity performance, all while operating off a low 3V or 3.3V supply voltage.

### IF Sampling

In addition to the higher sample rates, the analog input frequency range of ADCs has been greatly expanded as well. Long gone are the days when you could only use an ADC with input frequencies no greater than half the sample rate. Is Harry Nyquist turning over in his grave, you ask? Not exactly. It is still generally a good idea to limit the total signal bandwidth that gets digitized to one-half of the sample rate. However, nobody says that you have to

place that swath of bandwidth starting at DC. For example, with a 100MSPs ADC, you can digitize signals that are bandpass limited between 150MHz and 200MHz. The total bandwidth is still 50MHz, which is half the sample rate, but the input frequencies at which you operate are much higher.

In modern communications receiver systems, the practice described above is called IF sampling or undersampling. The RF input signal is mixed down to an IF frequency

using a downconverting mixer such as the LT<sup>®</sup>5557. This IF frequency is digitized, and all further processing is done digitally. To make this work for the high performance receiver systems in tomorrow's wireless basestations, the analog signal path that processes the IF frequency must be highly linear and low noise. The LTC6400 fills that need in a way that is efficient both in terms of board space and power.

*continued on page 3*

***In the high performance receiver systems of tomorrow's wireless basestations, the analog signal path that processes the IF frequency must be highly linear and low noise.***

***The LTC6400 fills that need in a way that is efficient in board space and power use.***



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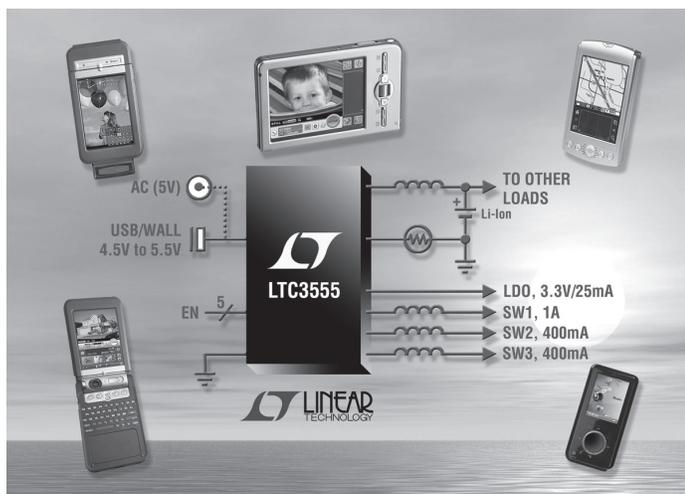
# Linear in the News...

## New Line of Power Management Chips

Linear Technology has announced a new line of power management chips that combines unique high performance power functions in compact formats for use in a wide range of portable electronic products. The new product line provides designers with simple, compact and reliable power management integrated circuits (PMICs) that combine the key power functions for products including media players, digital cameras, smart phones, personal navigation devices, PDAs, satellite radios, point-of-sale terminals, portable medical equipment and other lithium battery-powered devices.

"Today's designers are challenged to develop portable electronic products in increasingly short time-frames that are both highly compact and efficient in power delivery," according to Don Paulus, Vice President and General Manager of Linear Technology's Power Management Products. "Our new PMIC family provides a new level of performance by combining all the key power functions needed for each application."

Linear's new LTC35XX PMIC family was developed in response to the growing need for power management solutions for portable electronic products. The first device in Linear's new PMIC family, the LTC3555 USB Power Manager and Triple Step-Down DC/DC Converter, is now available, with other family members coming soon. The device incorporates a range of power management functions including a switching PowerPath™ manager, a stand-alone battery charger, three monolithic buck regulators and always-on LDO, controlled via an I<sup>2</sup>C interface, housed in a tiny 4mm x 5mm package. The switching PowerPath control feature seamlessly manages power flow between an AC/DC wall adapter, USB port, lithium-ion/polymer battery and system load, while maximizing power available from the USB and providing up to 1.2A to the system from the wall adapter. The chip's "instant-on" feature ensures system power, even with a dead or missing battery.



## Linear Opens Expanded Manchester, NH Design Center

Linear Technology announced the expansion of its Manchester, New Hampshire Design Center with the opening of a new 20,000 square foot design facility. The new Manchester Design Center facility, one of twelve centers focused on design of high performance analog integrated circuits, includes design facilities, lab and test development floor. With the company's growth, Linear has outgrown its prior New Hampshire Design Center facility and is relocating to a new, state-of-the-art design facility.

Lothar Maier, CEO of Linear Technology, stated, "The Manchester Design Center facility will allow us to grow our team of analog designers from the rich talent base in the New Hampshire/Boston area. Our new facility has a highly favorable location, close to world-class technical universities. We expect the Manchester Design Center to further increase its contribution of innovative products to serve the broad analog market, which will further fuel the company's growth."

Linear Technology's eleven other design centers are located in Boston, Massachusetts; Burlington, Vermont; Colorado Springs, Colorado; Dallas, Texas; Grass Valley, California; Phoenix, Arizona; Raleigh, North Carolina; Santa Barbara, California; Singapore; Munich, Germany, and at the company headquarters in Milpitas, California.

## Linear Technology Products Selected as Ultimate Products

*EE Times* in April published their latest list of Ultimate Products, selected by their readers and editors as best-in-class, and highlighted three Linear Technology products as top 10 products in the Power Products category.

The publication selected Linear's LTC4263 PSE Controller for Power over Ethernet and stated, "Linear Technology touts the current-sharing, stand-alone capabilities of its LTC4263 single-channel IC for Power over Ethernet (PoE) as unique among Power Sourcing Equipment (PSE) controllers."

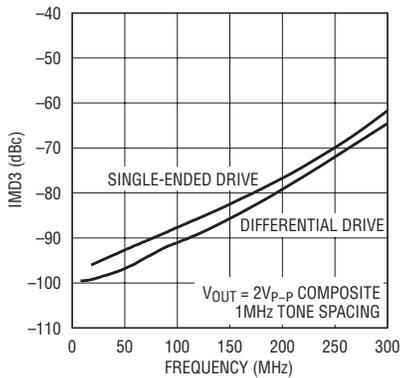
*EE Times* also selected Linear's LTM4601 and LTM4603  $\mu$ Module™ controllers as Ultimate products, with the headline, "Micromodules simplify point-of-load applications to 48 amps." The LTM4601 is a 12A DC/DC is a  $\mu$ Module with PLL, Output Tracking and Margining and the LTM4603 is a 6A DC/DC  $\mu$ Module with PLL, Output Tracking and Margining. *EE Times'* stated, "With capabilities far beyond the company's first-generation, high-voltage LTM4600 point-of-load DC/DC supply, the LTM4601 and LTM4603 series from Linear Technology, part of the  $\mu$ Module series of 'one-chip' power supplies, adds margining/tracking, remote-sense, expanded polyphase/paralleling capacity, and phase-locked loop synchronization functionality for advanced 6-48 amp designs. In addition, the new LTM4602 is a modified version of the LTM4600." 

LTC6400-20, continued from page 1

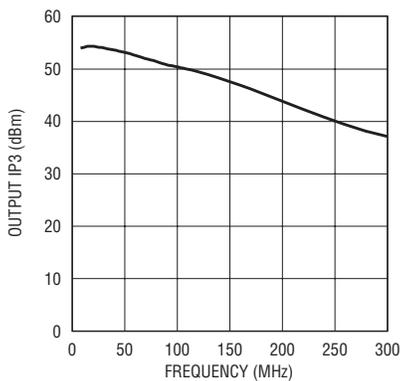
**Performance without Precedent**

Figure 1 shows the intermodulation distortion vs input frequency for a  $2V_{P-P}$  output signal. The LTC6400 achieves distortion at the  $-90\text{dBc}$  level up to  $140\text{MHz}$ , and at the  $-70\text{dBc}$  level up to a couple hundred MHz. Previously, this type of performance was only achievable using much higher power RF gain blocks (which typically aren't even differential). Figure 2 shows the equivalent OIP3 (3rd order output intercept point), which is an RF figure-of-merit that expresses output linearity irrespective of signal level.

Besides distortion, the other key performance requirement of an IF ADC Driver is low noise contribution. The LTC6400 is based on a differential op amp with a very quiet  $1\text{nV}/\sqrt{\text{Hz}}$  input noise density. The internal  $200\Omega$  differential input resistors inevitably add some noise of their own, resulting in a



**Figure 1. The LTC6400 maintains low intermodulation distortion up to hundreds of MHz, allowing for high performance IF sampling applications**



**Figure 2. The LTC6400 Equivalent Output-IP3 is in excess of 50dBm up to 100MHz, and in excess of 40dBm up to 250MHz**

**The LTC6400 differential amplifier is manufactured on an advanced complementary bipolar silicon-germanium (SiGe) process, which allows for faster transistors. At the core of the LTC6400 is a very high speed differential op amp. The combination of fast transistors and streamlined circuit topology results in an op amp with a gain-bandwidth product in excess of 3GHz relative to a unity-gain stable transfer function.**

$2.1\text{nV}/\sqrt{\text{Hz}}$  total input referred noise density.

In RF terms, when terminated in a matched  $200\Omega$  system, this translates to a noise figure of only 6.1dB. Since the LTC6400 is typically the last stage before the ADC in a receiver line-up there are other gain blocks that precede it. To refer a component's noise contribution to the actual input of the entire receiver, you divide it by the gain that precedes it. Therefore,

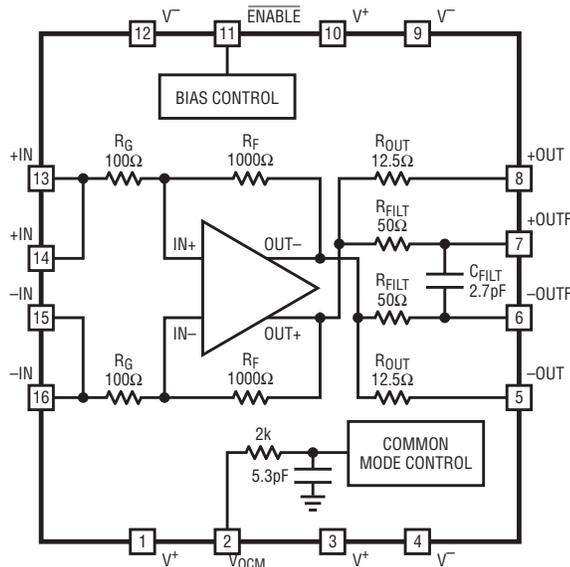
the low 6.1dB noise figure of the LTC6400 allows for very low noise receiver designs.

Another way to look at noise is in terms of SNR (signal-to-noise ratio). The LTC6400-20 output noise density is  $21\text{nV}/\sqrt{\text{Hz}}$  (because the gain is  $10\text{V}/\text{V}$ ). If you limit the input signal bandwidth to a generous  $50\text{MHz}$ , this amounts to  $148\mu\text{V}_{\text{RMS}}$  of integrated noise. This allows for a 74dB SNR relative to a  $2V_{P-P}$  full-scale signal, compatible with popular 14-bit ADCs such as the LTC2249.

**A Look under the Hood**

The LTC6400 differential amplifier is manufactured on an advanced complementary bipolar silicon-germanium (SiGe) process. Because germanium atoms are larger than silicon atoms, selectively adding some germanium to an otherwise silicon process causes strains within the material's crystalline structure. This strain actually results in beneficial electrical properties, such as higher carrier mobility and a more precise control of the base-width, allowing for faster transistors.

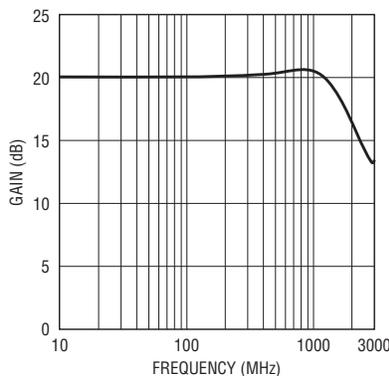
Figure 3 shows a block diagram of the LTC6400. At its core is a very high speed differential op amp. The combination of fast transistors and streamlined circuit topology results in an op amp with a gain-bandwidth



**Figure 3. The LTC6400 combines a very high speed differential op amp with on-chip feedback resistors**

product in excess of 3GHz relative to a unity-gain stable transfer function. Furthermore, all feedback resistors are integrated. In addition to the obvious space savings, integrating the feedback network results in several design benefits:

- ❑ The sensitive summing nodes at the immediate inputs of the op amp are not exposed to the vagaries of board layout, which allows us to carefully control the amount of parasitic capacitance seen at that node. Otherwise, even as little as 100 femto-Farads at this node (for example due to board traces, package pins, or bond pads) would cause unwanted poles in the loop-gain of the feedback network.
- ❑ If the feedback resistors were off-chip, two sets of bond wires (at the op amp outputs and inputs) would be in the feedback loop. On chip resistors eliminate bond wire or lead inductance associated with the op amp inputs, and those at the op amp outputs are outside of the feedback loop. At frequencies of 3GHz and above, even a small 1nH of inductance exhibits significant impedance and phase shift, which would again limit the achievable speed and performance.
- ❑ Since the gain is fixed and higher than unity, we can internally de-compensate the op amp to achieve the maximum possible open-loop gain for a given closed-loop configuration. The more open-loop gain, the better the



**Figure 4: The op amp inside the LTC6400-20 is internally decompensated, so that even though the closed loop gain is 10V/V (20dB), the closed loop -3dB bandwidth is still an impressive 1.8GHz**

feedback action can suppress non-linear components. In addition, this compensation technique preserves a wide -3dB bandwidth even though the gain is high, as shown in Figure 4.

## Application Example

Figure 5 shows a typical application of the LTC6400 driving the LTC2208, a 16-Bit 130MSPS ADC. In this case, the input signal is single-ended, and applied to the +IN input of the LTC6400 through a DC-blocking capacitor. (With a little bit of care, the signal could also be DC-coupled, so long as the DC voltage is within the input common mode range of the amplifier.) As can be readily observed from Figure 3, the input impedance of the LTC6400-20 is 200Ω differential. The 66.5Ω input resistor changes the total input impedance to 50Ω, to provide a match to a 50Ω source impedance. Alternatively, a 1:4 transformer may

be used for matching the amplifier to a 50Ω load. In other cases, the source impedance may already be 200Ω and no additional components would be necessary. The 29Ω resistor placed at the -IN input provides a balanced termination for the internal op amp.

The LTC6400 is powered from the same 3.3V as the ADC, saving the need for another power supply rail. It could do the same with a 3V rail. Other driver solutions require 5V or more to drive ADCs to full-scale with high performance.

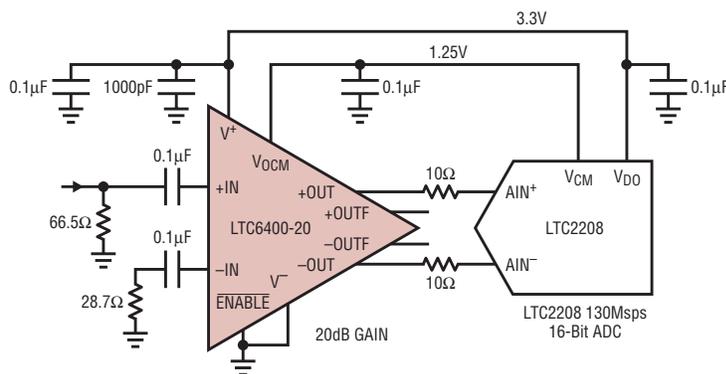
The LTC2208 family of ADCs wants to see its inputs swing centered around a 1.25V common mode voltage. The LTC6400 makes this easy: simply connect the V<sub>CM</sub> pin of the ADC to the V<sub>OCM</sub> pin of the LTC6400, and the amplifier's internal common-mode feedback loop ensures that the outputs swing centered around the value applied to V<sub>OCM</sub>. For ADCs that prefer a 1.5V common-mode voltage, the interface is the same.

## Related Parts

The LTC6401-20 is a lower power version of the LTC6400-20. The LTC6401-20 consumes only 45mA at 3V or 3.3V. Both amplifiers are pin-compatible and have the same low noise performance. The LTC6401 maintains excellent linearity up to 140MHz, while consuming only half the power of the LTC6400.

## Conclusion

By combining a new SiGe process with careful, innovative design, the LTC6400 offers unprecedented performance at high frequencies, all while operating at a low 3V or 3.3V supply voltage. A tiny 9mm<sup>2</sup> leadless package, along with a minimal number of external components, lets you place the driver right at the ADC inputs, providing the best performance and compact board layout. The differential outputs are uniquely optimized to directly drive state-of-the-art high speed ADCs with high linearity, while the low input-noise preserves the sensitivity of a high performance receiver system.



**Figure 5. The LTC6400 can drive high performance ADCs with a minimum of external components**

# 12-, 10-, and 8-Bit DACs with Integrated 10ppm/°C Reference in 2mm × 2.1mm SC70

by Kevin Wrenner, Troy Seman and Mark Thoren

## Introduction

Because the output voltage range of a DAC is directly proportional to its reference voltage, the accuracy of the reference directly impacts the accuracy of the output. Despite the critical nature of the reference voltage, it is often overlooked, and simply tied to a power supply rail. This makes the DAC output track the power supply—including its inaccuracies and noise, which may be unspecified and quite large.

In the LTC2630 family of small-footprint DACs, a high performance voltage reference is built in (Figure 1), eliminating the need for an external reference. The LTC2630 provides an unprecedented combination of accuracy, small size, integrated reference and ease of use, making it ideal for applications from general-purpose voltage adjustment in analog signal conditioning circuits to high accu-

racy industrial controls. An H-grade version that operates over a -40°C to +125°C temperature range is available for demanding industrial, military, or automotive applications.

## Full Scale Defined by Integrated Reference or Supply

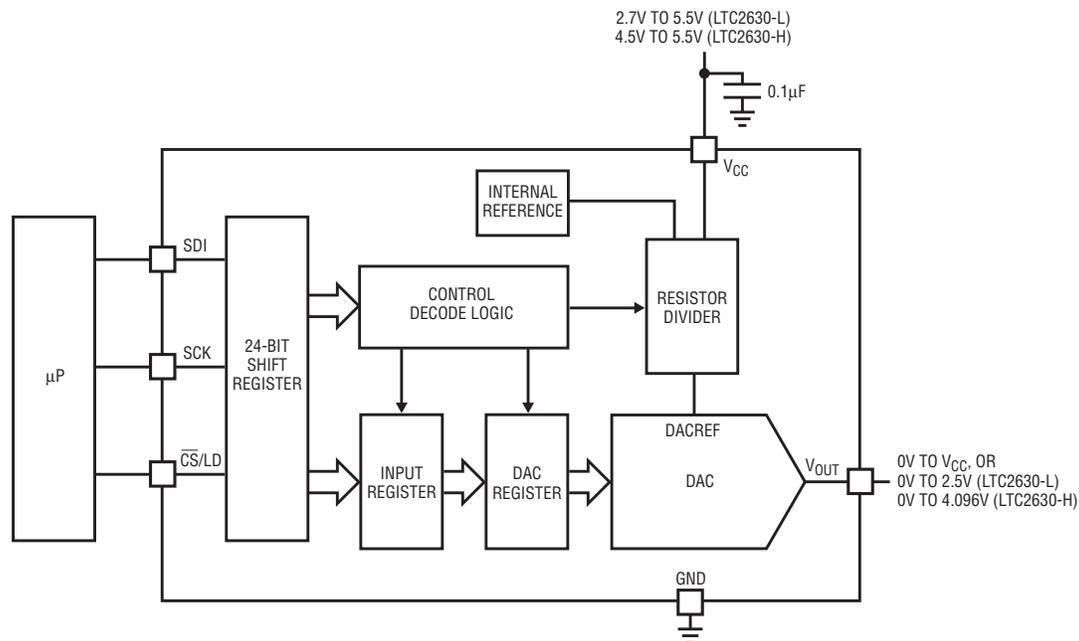
The LTC2630's integrated reference provides a full-scale voltage that is

low drift ( $\pm 10\text{ppm}/^\circ\text{C}$ ) and insensitive to supply voltage variations. The LTC2630-L has a full-scale output of 2.5V and operates from a single 2.7V to 5.5V supply. The LTC2630-H has a full-scale output of 4.096V and operates from a 4.5V to 5.5V supply. When configured in supply-as-reference mode, the output of the LTC2630 can swing rail-to-rail referenced to the input supply.

## Tiny SC70 Footprint and Ultralow Power

The LTC2630 fits the 12-, 10-, or 8-bit DAC and internal reference in an ultracompact 6-lead SC70 package (2mm × 2.1mm). Power consumption is low, too. When operating in internal reference mode, supply current is just 180 $\mu\text{A}$  at 3V. Performance of the DAC, however, is anything but low.

*The LTC2630 offers an unprecedented combination of accuracy, small size, integrated reference and ease of use, making it ideal for a wide range of applications.*



**Figure 1.** The LTC2630 integrates a high performance rail-to-rail amplifier, 10ppm/°C reference, and double-buffered input data path in an SC70 package.

**Outstanding DAC Performance**

**Linearity: at 12-Bit Accuracy, DNL and INL are Guaranteed  $\pm 1$ LSB**

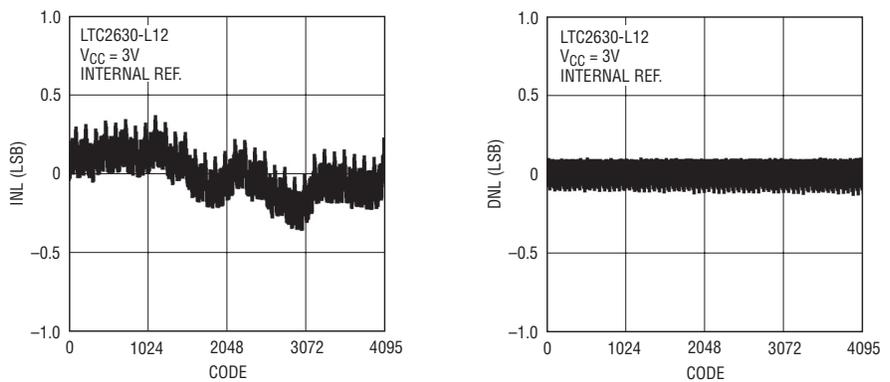
The LTC2630 family uses Linear Technology's proprietary, inherently monotonic voltage interpolation architecture, the benefits of which can be seen in Figure 2. For the LTC2630A-12, the DNL is  $\pm 0.2$  LSB, the INL is  $\pm 0.5$ LSB, and both are guaranteed to be less than  $\pm 1$  LSB over the full operating temperature range of the part. For the LTC2630-12, DNL and INL are guaranteed to  $\pm 1$  LSB and  $\pm 2$  LSB over temperature, respectively. At 10 bits (LTC2630-10), DNL and INL are guaranteed less than  $\pm 0.5$  LSB and  $\pm 1$  LSB over temperature, respectively. At 8 bits (LTC2630-8), both are guaranteed less than  $\pm 0.5$  LSB over temperature.

**Predictable and Usable Output Range**

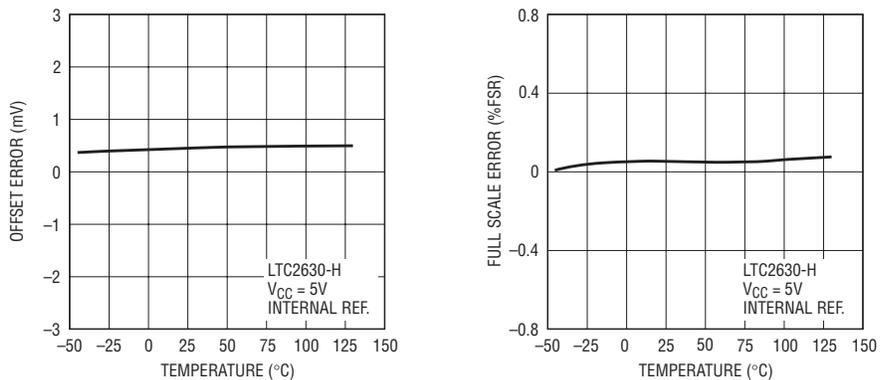
Over its rated temperature range, the LTC2630 has a maximum offset of  $\pm 5$ mV. The low offset enables a starting code voltage closer to 0V than competing devices. When full scale is set by the internal reference, the full-scale error voltage is just  $\pm 0.8\%$  of the full-scale range (FSR), and linearity is guaranteed to the upper code limit. The invariance of these parameters over temperature is shown in Figure 3. Together, low offset and low full-scale error define a predictable output range and maximize the number of usable codes.

**Excellent Load Regulation Means Hidden Error is Reduced**

The LTC2630's output buffer is guaranteed to be capable of sourcing and sinking 5mA at 2.7V and 10mA at 4.5V. Its high gain amplifier holds the output resistance at only  $0.1\Omega$  ( $0.156\Omega$  max) despite having a single GND pin. Figure 4 shows how this minimizes output voltage error due to DC loading—only 0.1 LSB per mA of load current ( $0.16$  LSB/mA max) for the LTC2630-12H and  $0.13$  LSB per mA ( $0.256$ LSB/mA max) for the LTC2630-12L. In comparison, the lowest DC



**Figure 2. Integral and differential nonlinearity in internal reference mode. The LTC2630's excellent DNL guarantees its monotonicity.**



**Figure 3. Low-drift offset error voltage and full-scale error voltage.**

output impedance of any competitor is  $0.5\Omega$ , easily introducing five times greater load-induced error.

**Easy Operation**

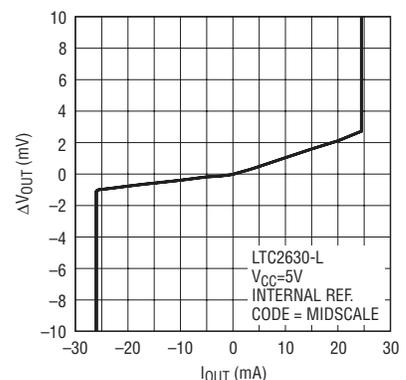
The LTC2630 family operates off a single supply and can drive loads up to  $500$ pF without any stability concerns.

Its simple SPI/MICROWIRE-compatible 3-wire interface can be operated at clock rates of up to  $50$ MHz. Setup and hold times of only  $4$ ns allow problem-free operation in optoisolated and other applications having slow edge rates. The internal data registers are double-buffered, allowing simultaneous updating of multiple devices in a system. All three parts in the LTC2630 family use the same 24-bit load sequence (32-bit is also supported). There are six command codes for selecting internal or supply reference modes, powering down, writing to the input register, updating the DAC register and performing a combined write and update.

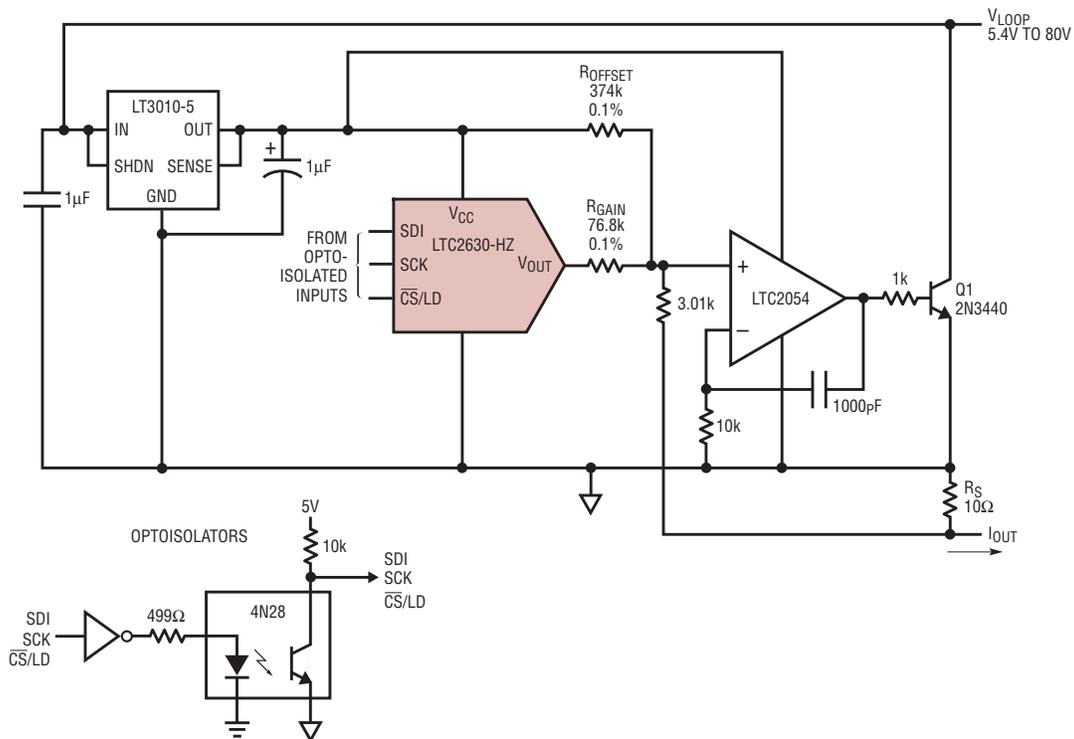
**Other Features**

At power up, the internal reference is selected by default, and the code is reset to either midscale (LTC2630-M) or zero (LTC2630-Z). Internal circuitry holds the output glitch to less than  $5$ mV if the supply is ramped no faster than  $1$ V/ms.

The LTC2630 can be placed in a power-saving mode in which current



**Figure 4. Load regulation. The high drive output buffer is guaranteed to source and sink 5mA at 3V, and 10mA at 5V, well inside the bounds of current limiting. Output resistance of only  $0.1\Omega$  keeps the error contributed by DC loading to a minimum.**



**Figure 5. Optoisolated 4mA to 20mA process controller. This circuit digitizes an output current for use in an isolated control loop.**

draw at 5V is reduced to below 1.8µA (5µA for H-grade operating at 125°C). Upon exiting power down mode, the output settles at midscale to 12-bit accuracy in 18µs.

### Optoisolated 4mA to 20mA Process Controller

LTC2630 is well-suited to industrial applications, including control loops. Figure 5 shows an optically-isolated,

digitally-controlled 4mA to 20mA transmitter using the LTC2630HZ. The transmitter circuitry, including optoisolation, is powered by the loop voltage, which has a wide 5.4V to 80V range. The 5V output of the LT3010-5 sets the 4mA offset current and the DAC digitally controls the 0mA to 16mA signal current. The supply current for the regulator, DAC and op amp is well below the 4mA budget

at zero scale.  $R_S$  senses the total loop current, which includes the quiescent supply current and additional current through Q1. Note that at the maximum loop voltage of 80V, Q1 dissipates 1.6W when  $I_{OUT}$  is 20mA, so it must have an appropriate heat sink.

The values of  $R_{OFFSET}$  and  $R_{GAIN}$  are as close to ideal as possible using 0.1% resistors to meet the 4mA–20mA design objective. Alternatively,  $R_{OFFSET}$  can be a 365k, 1% resistor in series with a 20k trim pot and  $R_{GAIN}$  can be a 75.0k, 1% resistor in series with a 5k trim pot. If the application calls for a high speed serial bus, use 6N139 rather than 4N28 optocouplers.

### Conclusion

The LTC2630 is a family of single voltage output DACs in 6-lead SC70 packages with integrated references. Each DAC can provide its own accurate full-scale voltage and can operate rail-to-rail referenced to the input supply. Twelve options are available in various combinations of accuracy (12-, 10-, and 8-bit), full-scale voltage (2.5V or 4.096V), and power on reset value (zero or midscale); see Table 1. 

**Table 1. Available part options. The LTC2630 is offered in twelve combinations of full-scale voltage, power-on reset, and accuracy.**

	Full-Scale Reference	Power-On Reset Code	Accuracy (Bits)	V <sub>CC</sub> (V)
LTC2630-LM	2.5V	Midscale	12 10 8	2.7–5.5
LTC2630-LZ	2.5V	Zero	12 10 8	2.7–5.5
LTC2630-HM	4.096V	Midscale	12 10 8	4.5–5.5
LTC2630-HZ	4.096V	Zero	12 10 8	4.5–5.5

# 3 $\mu$ A Quiescent Current LDO Improves Efficiency for Low Power Circuits in Industrial, Automotive and Battery-Powered Systems

by Sam Rankin

## Introduction

Many electronic systems spend much of their time in an idle state, waiting for something to happen. Industrial remote monitoring systems and keep-alive circuits are but two examples. Many of these systems depend on battery power, so a high efficiency power supply is paramount to preserve battery life. Efficiency during quiescent state is of particular importance since active operation may draw milliamps while quiescent operation only microamps. Small size and reverse output and input protection capabilities are also desirable features in a power supply. This is a demanding combination of power supply requirements, but there is an easy way to satisfy them with one device.

## Ultralow Quiescent Current PNP LDO

Figure 1 shows a typical application for the LT3009, a 3 $\mu$ A quiescent current low dropout linear regulator in tiny 2mm  $\times$  2mm DFN and 8-lead SC70 packages. Its ultralow 3 $\mu$ A quiescent current is well controlled—it does not rise excessively in dropout as happens with many regulators. Quiescent current is less than 5% of

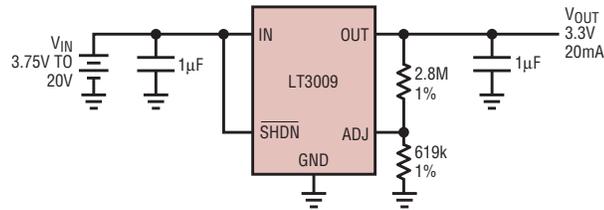


Figure 1. New 3 $\mu$ A quiescent current low dropout regulator

output current at 20mA  $I_{OUT}$ , even in dropout (Figure 2).

The LT3009 can supply up to 20mA from input supplies ranging from 1.6V to 20V to output voltages ranging from 0.6V to 19.5V. Dropout voltage on the LT3009 is only 280mV while delivering up to 20mA of output current. It can be put into a low power shutdown state by pulling the SHDN pin low. In shutdown state, the already low quiescent current is reduced to the leakage currents of the internal transistors. This leakage, typically a few nA at room temperature, stays below 1 $\mu$ A over the entire operating temperature range. Low quiescent current and tiny package size does not translate into poor performance in the LT3009. The LT3009 features industry leading load, line, and temperature regulation (see Figures 3, 4 and 5)

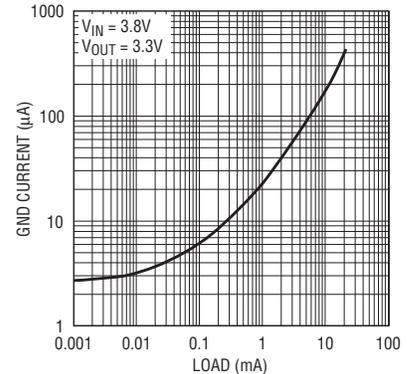


Figure 2. GND Pin current vs  $I_{LOAD}$

Aside from the output voltage setting resistors, the only external components required are input and output bypass capacitors. Internal frequency compensation in the LT3009 stabilizes the output for a wide range of capacitors. A minimum of 1 $\mu$ F of

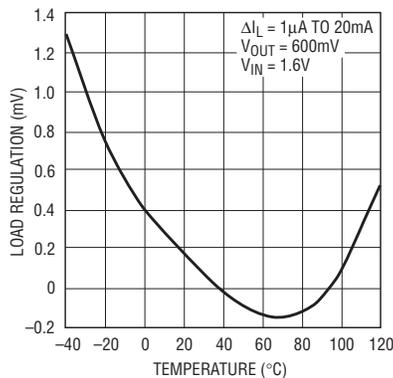


Figure 3. Load regulation vs temperature

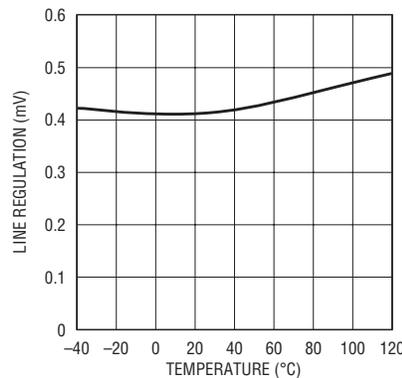


Figure 4. Line regulation vs temperature

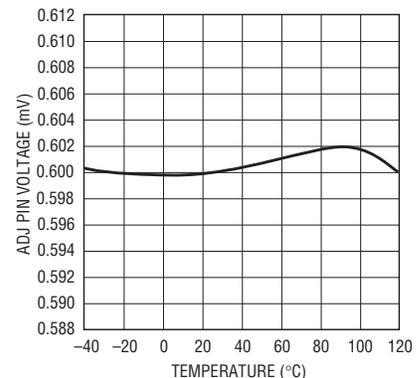


Figure 5. Output voltage vs temperature

output capacitance is required for stability, and almost any type of output capacitor can be used. Even small ceramic capacitors with low ESR can be used without the additional series resistance commonly required with other regulators. The combination of small package size and the ability to use small ceramic capacitors enable the LT3009 to fit almost anywhere.

The LT3009 has a number of protection features to safeguard itself and sensitive load circuits. Should the input voltage become reversed (due to a battery inserted backwards or a fault on the line, for example), current flow from the IN pin is limited by a 100k resistance and no negative voltage is seen at the load. No external protection diodes are necessary when using the LT3009. With a reverse voltage from output to input, the LT3009 acts as though it has a 500k limiting resistor in series with two diodes from output to input to limit reverse current flow. For dual-supply applications where the regulator load is returned to a negative supply, the OUT and ADJ pins can be pulled below ground (by up to a 20V input-to-output differential) while still allowing the device to start and operate. The LT3009 also includes protection features found standard on linear regulators such as current and thermal limiting.

### The Ideal Solution for Remote Monitoring

The LT3009 provides an optimum solution for remote monitoring applications. The duty cycle of many of these applications is very short—they spend most of their time in shutdown, waking briefly to take and communicate measurements, then returning immediately to shutdown. Aside from

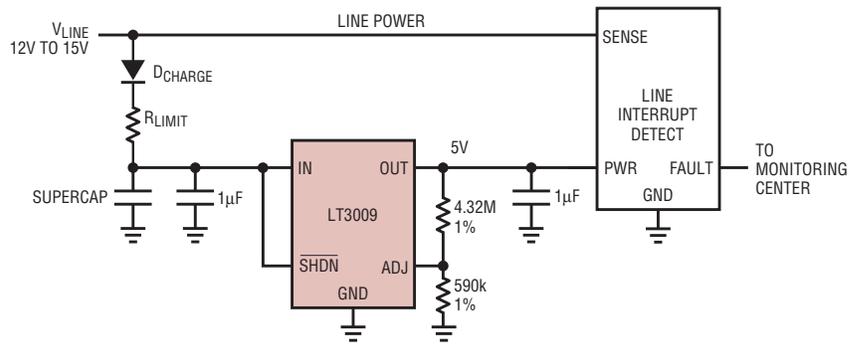


Figure 6. Typical last-gasp circuit

the typical supply regulation requirements required by sensitive analog circuitry (tight supply regulation, quiet supply, load protection, etc.), the principle supply requirement is low quiescent power consumption. With its 3µA quiescent current coupled with industry leading supply regulation capability and myriad of protection features, the LT3009 fits the bill.

A typical remote monitoring application used frequently in utility meters is a “last-gasp” circuit, shown in Figure 6. In this application, a 12V to 15V supply derived from line power charges a large capacitor (SuperCap) through a diode and a current limiting resistor. This stored voltage on the SuperCap provides input voltage for the LT3009. The LT3009 provides a quiet, well-regulated 5V supply to the analog fault detection circuits as well as a digital communication module used to send distress signals to the remote monitoring center. The fault detection circuitry is typically active for only a few hundred milliseconds every 15-minute detection cycle. In the event of a line failure, the ultralow quiescent current of the LT3009 enables the SuperCap to provide enough power to the

fault detection and communications circuitry for several detection cycles.

The 3µA quiescent current of the LT3009 reduces the required size and cost of the SuperCap while simultaneously extending the life of the detection and communications circuits after line failure. Additionally, with its output regulation of ±2% over load line and temperature, the LT3009 can do double duty as a highly accurate voltage reference for the fault detection circuits.

### An Excellent Choice for Keep-Alive Power Supplies

Switching power supplies provide robust local low voltage/high current power from high voltage rails, but switching power supplies are overly complex for the low power keep-alive circuits that typically run only a few milliamps of current. There are many such low current applications in industrial, monitoring, security systems, smoke detectors, and other always-on circuits. For many of these applications, the LT3009 provides a relatively simple and inexpensive solution.

A typical keep-alive application is shown in Figure 7. A 12V rail powers a keep-alive circuit for monitoring or other purposes. Low quiescent current is critical here to reduce battery drain. A battery backup keeps the output alive when a fault on the input occurs. Should a fault on the 12V rail occur, the battery backup takes over. The internal protection of the LT3009 limits current flow from the output back to the input, removing the need for protection diodes.

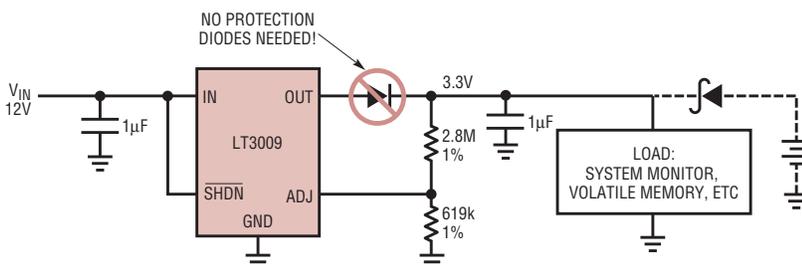


Figure 7. Typical keep-alive power supply

continued on page 24

# Triple Output LED Driver Delivers 3000:1 Dimming Ratio in Buck, Boost or Buck-Boost Mode

by Bin Zhang

## Introduction

The LT3496 is a triple output DC/DC converter designed for high performance, True Color PWM™ dimming in multichannel LED lighting applications. By integrating three independent driver channels, the LT3496 provides a space-saving and cost-efficient solution to drive multiple LED strings. Figure 1 shows a 50W LT3496 3-channel LED driver that occupies 350mm<sup>2</sup> and with a sub-1.5mm profile.

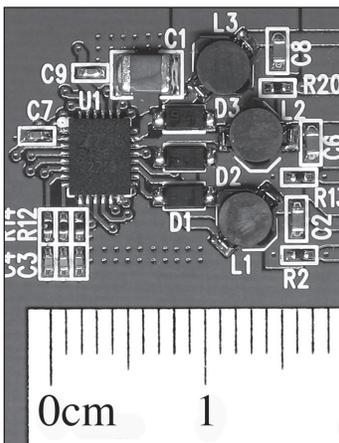


Figure 1. A complete LT3496 LED driver fits into 350mm<sup>2</sup>

ratio in buck, boost, or buck-boost configurations. The 45V capability of the internal power switch, 3V–40V input voltage range, and adjustable frequency result in reliable operation over a wide range of supply and output voltages. Applications for the LT3496 include RGB lighting, billboards and large displays, automotive and aviation lighting, and constant-current sources.

## High Side LED Disconnect with High Side Current Sensing for System Versatility, Simplicity and Reliability

The LT3496's high side LED disconnect and high side current sensing enable 3000:1 dimming control in buck, boost, or buck-boost configurations. No traditional LED driver can match the simplicity and high PWM

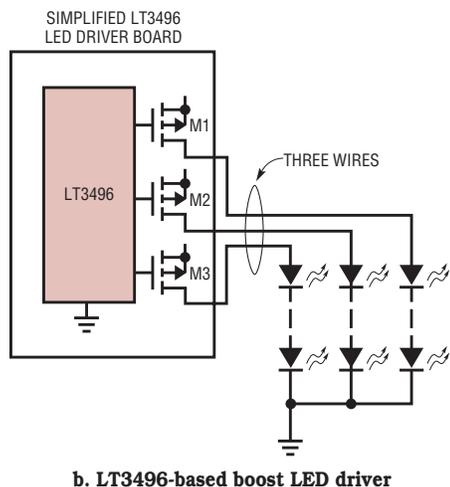
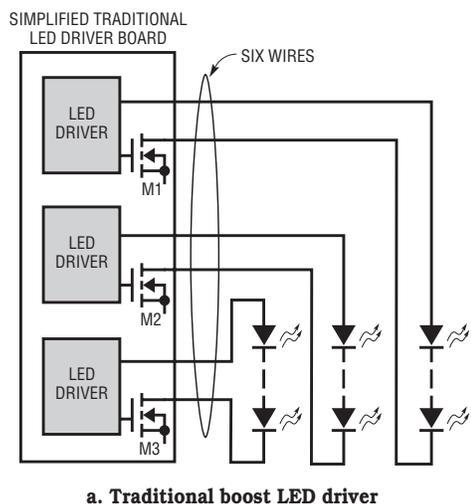


Figure 2. An LT3496-based boost LED driver requires half as many wires as a traditional boost LED driver

The LT3496 features high side current sensing and built-in gate drivers for PMOS high side LED disconnect (patent pending). These two features give the LT3496 its versatility, allowing it to drive LED's to high PWM dimming

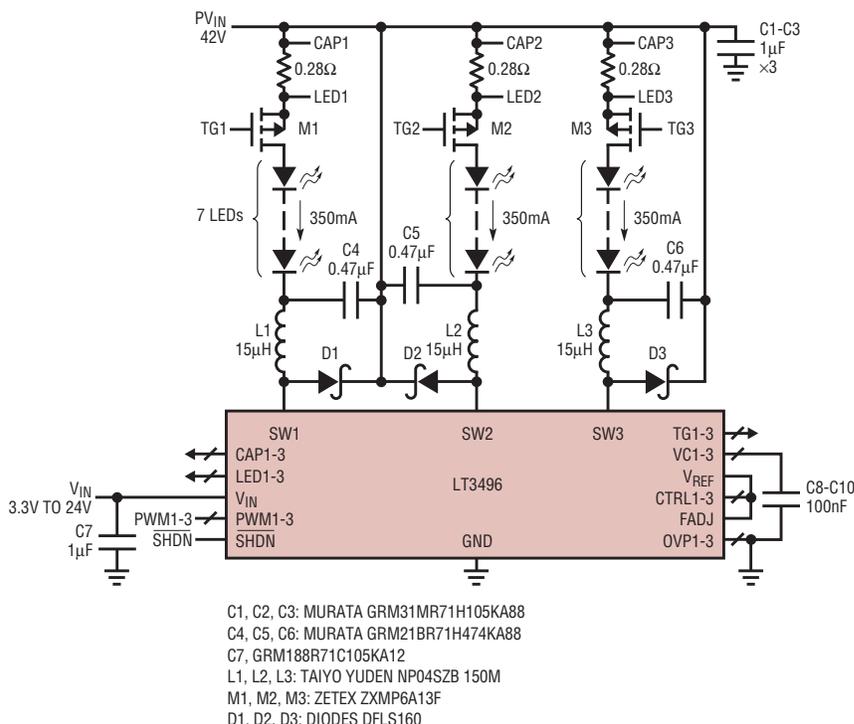
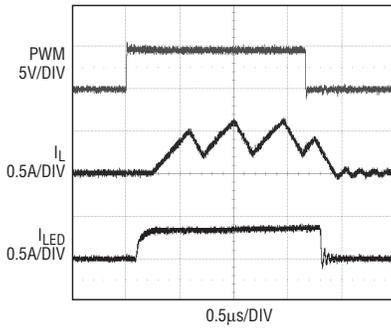


Figure 3. The LT3496 RGB driver for large TFT LCD TVs



**Figure 4. 5000:1 dimming waveforms for the application circuit of Figure 3**

dimming performance of LT3496, especially in buck-boost mode. Implementation of a high side disconnect switch with traditional LED drivers is possible, but uses many additional components, has slow response and burns extra power.

Because the LED disconnect and current sensing are on the high side of each LED string, the low sides of the LED strings can be tied together in boost or buck-boost mode to reduce the number of wires returning to the LED driver. In a boost configuration, each of the low side connections can be returned to ground anywhere, allowing a simple 1-wire LED connection

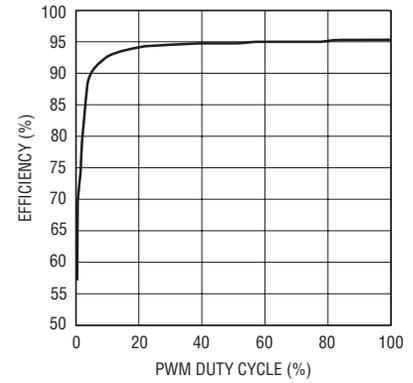
for each LED string. Traditional LED drivers employ a low side LED disconnect approach, in which both the high side and the low side of each LED string must connect to the LED driver. Figure 2a shows simplified traditional boost LED drivers, where M1–M3 are LED-disconnect NMOS switches. Figure 2b shows a simplified LT3496 triple boost LED driver, where M1–M3 are LED-disconnect PMOS switches. The LT3496 solution removes three wires, increasing system simplicity and reliability. These advantages will become increasingly important as the channels are multiplied in high performance displays.

### Applications

#### Buck Mode LED Driver

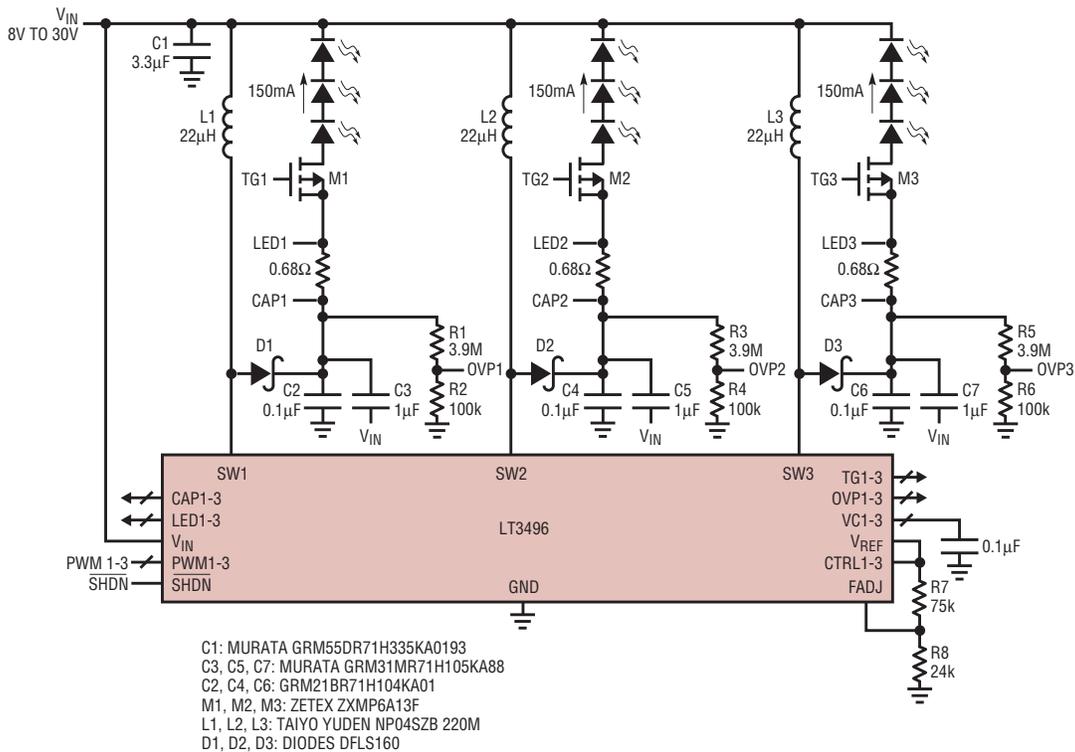
The LT3496 can be configured as a buckmode LED driver for applications where the LED voltage is lower than the supply voltage. Figure 3 shows an LT3496 RGB driver for a large TFT LCD TV.

The three LT3496 channels operate independently, but function in the same way. For simplicity, the PWM operation of channel 1 is described



**Figure 5. Efficiency of the application circuit of Figure 3**

here. If the PWM1 pin is pulled low, M1 is turned off, disconnecting the LED string of channel 1 and stopping the current draw from output capacitor C4. The VC1 pin is also disconnected from the compensation capacitor C8. C4 stores the state of the LED voltage and C8 stores the state of the LED current until PWM1 is pulled up again. This leads to a highly linear relationship between pulse width and output light, a large and accurate dimming range, and high efficiency. At 120Hz PWM frequency, the PWM control of the circuit allows 5000:1 dimming as shown in Figure 4. Figure 5 shows the



**Figure 6. Buck-boost mode LED driver for automotive lighting**

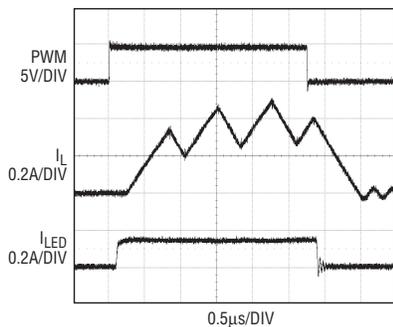
efficiency as a function of the PWM duty cycle.

**Buck-Boost Mode LED Driver**

In some LED applications, the desired supply voltage range and LED voltage range overlap, thus requiring buck-boost mode configuration. Figure 6 shows a LT3496 buck-boost mode LED driver for automotive lighting. The LED voltage is 9V–12V and the automobile battery voltage is 8V–30V. R1–R6 set the overvoltage protection voltage at 40V to guarantee the voltages of SW1–SW3, CAP1–CAP3, LED1–LED3, and TG1–TG3 pins are below the maximum rating voltage. R7–R8 set the switching frequency at 1.3MHz to limit the LT3496 power dissipation and ensure that a junction temperature of 125°C is not exceeded. Figure 7 shows the 3000:1 PWM dimming waveforms at 120Hz PWM frequency.

**Boost LED driver**

The LT3496 can be configured as a boost LED driver for the applications where the LED voltage is higher than



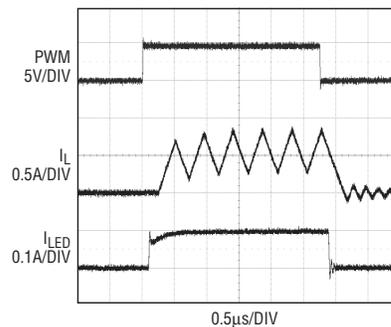
**Figure 7. 3000:1 dimming waveforms for the application circuit of Figure 6**

the supply voltage. Figure 8 shows a LT3496 boost LED driver for automotive lighting. D4, Q1–Q3, and R1–R4 create the battery surge voltage protection circuits to protect the LED string from being damaged by a battery surge voltage. The zener breakdown voltage of D4 is chosen to be lower than the LED voltage. When the VIN surge voltage increases to be close to the LED voltage, D4 breaks down and turns on Q1–Q3. Q1–Q3 pull PWM1–3 low and M1–M3 are turned off immediately to disconnect the LED strings from the LED driver.

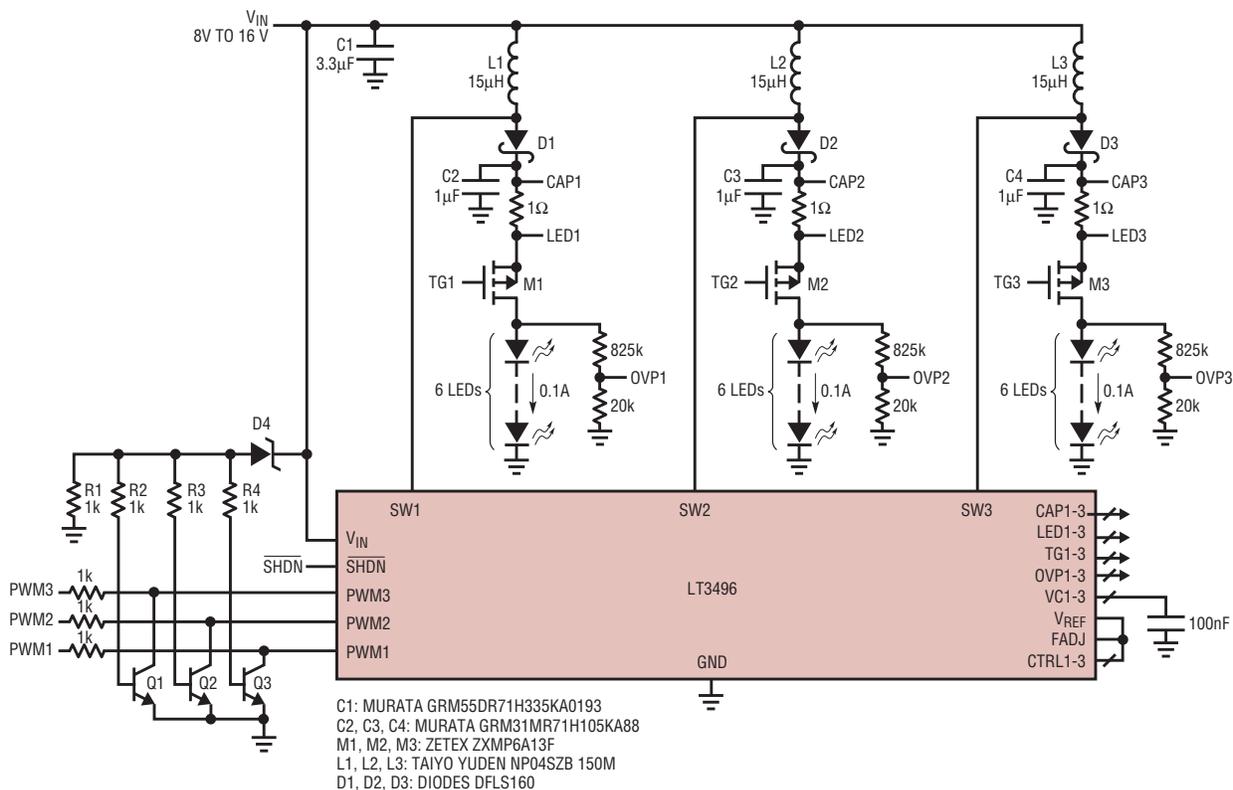
Figure 9 shows the 3000:1 PWM dimming waveforms at 120Hz PWM frequency.

**Conclusion**

The LT3496 provides a compact, low cost, high reliability, and high efficiency solution to multichannel LED lighting. With the capability of operating in buck, boost and buck-boost mode, the LT3496 LED driver delivers 3000:1 True Color PWM™ dimming ratio over a wide range of supply and output voltages.



**Figure 9. 3000:1 dimming waveforms for the application circuit of Figure 8**



**Figure 8. Boost mode LED driver with battery surge voltage protection for automotive lighting**



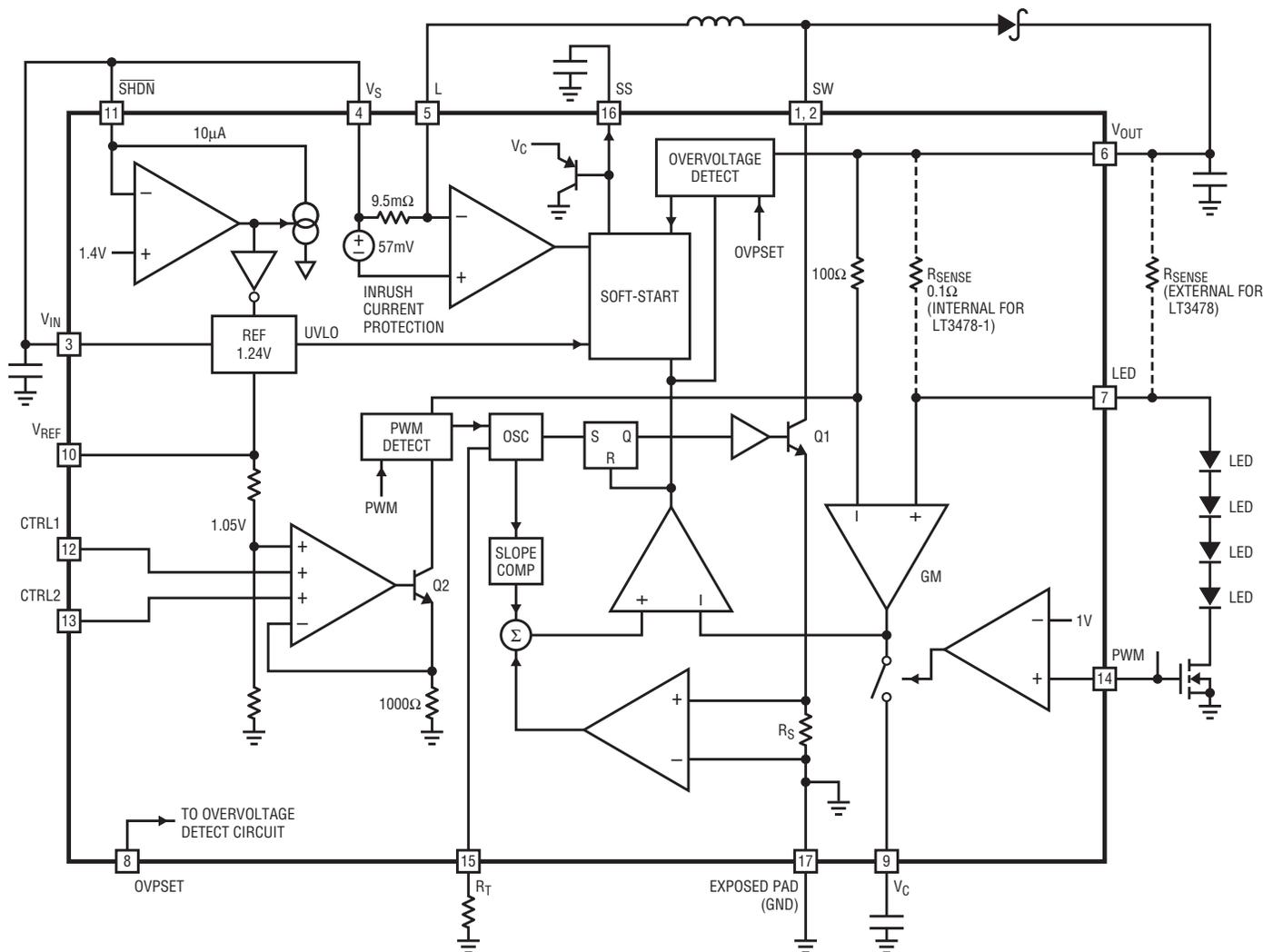


Figure 2. LT3478 and LT3478-1 block diagram

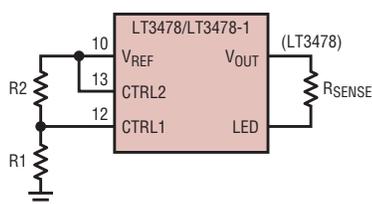


Figure 3. Programming maximum LED current

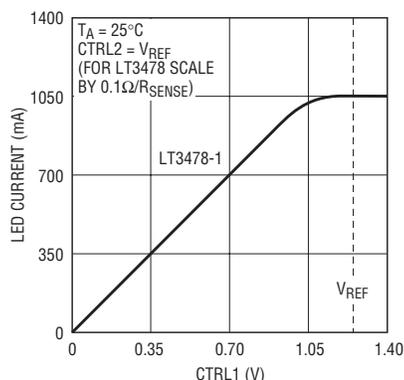


Figure 4. LED current vs CTRL1 voltage

$V_{REF}$  (see Figure 3), from an external voltage source, or by connecting it directly to the  $V_{REF}$  pin for maximum current. Figure 4 shows LED current versus CTRL1 pin voltage.

### Temperature-Based Derating of the Maximum LED Current

To ensure optimum reliability, LED manufacturers specify curves of maximum allowed LED current versus temperature (Figure 5). If the LED current is not derated relative to temperature, it is possible to permanently damage the LED.

The LT3478 and LT3478-1 enable temperature derating via the CTRL2 pin. Simply connect CTRL2 to  $V_{REF}$  via a temperature-dependent resistor divider as shown in Figure 6. As the temperature rises, the voltage at

CTRL2 falls. When CTRL2 falls below CTRL1, the voltage at CTRL2 takes over in setting the maximum LED current (Figure 7).

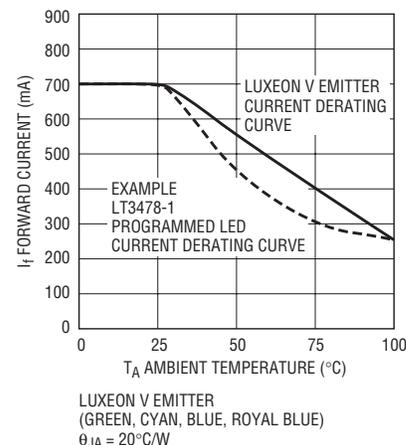
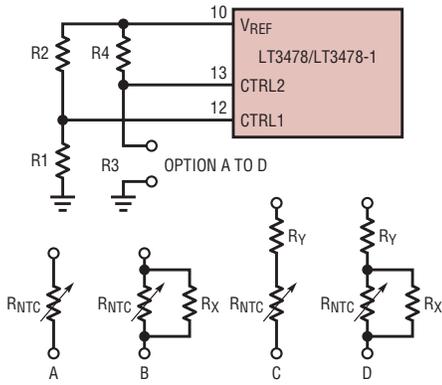


Figure 5. LED current derating curve vs ambient temperature

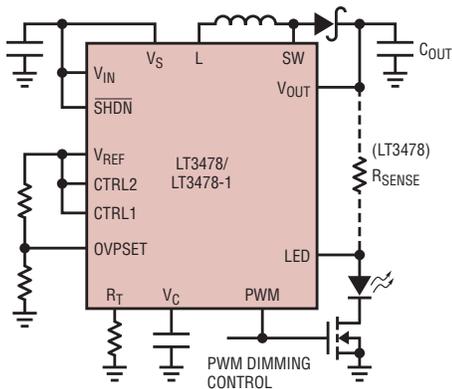


**Figure 6. Programming LED current derating curve vs temperature ( $R_{NTC}$  located on LED's circuit board)**

The temperature at which LED current begins to decrease and the rate of decrease are selectable by the resistor network/values chosen. Table 1 lists several NTC resistor manufacturers. Murata Electronics notably provides an online simulator to select the required resistor combinations as shown in Figure 6 including a catalog describing the NTC resistor specifications. Figure 5 shows an example of LT3478-1 programmed LED current falling versus temperature using the option C, shown in Figure 6, with  $R_4 = 19.3k$ ,  $R_Y = 3.01k$  and  $R_{NTC} = 22k$  (NCP15XW223J0SRC). A more detailed description of how to determine these values by hand calculation is given in the LT3478 and LT3478-1 data sheet.

### Analog Dimming

Many LED applications require accurate brightness control. LED brightness can be reduced by simply decreasing the programmed LED



**Figure 8. PWM dimming control**

**Table 1. NTC resistor manufacturers/distributors**

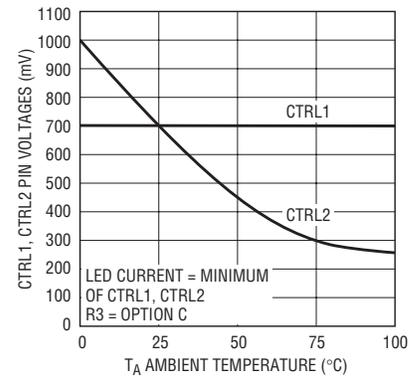
Manufacturer	Contact
Murata Electronics North America	www.murata.com
TDK Corporation	www.tdk.com
Digi-Key	www.digikey.com

current, but reducing the operating current of the LED changes the color of the LED. This method is known as analog dimming and is available in the LT3478 and LT3478-1 by reducing the voltage at the CTRL1 pin to as low as 0.1V (10:1 dimming from 1V). If color preservation is important, then PWM dimming is a better option.

### PWM Dimming

PWM dimming (Figures 8 and 9) yields high dimming ratios with no current-related LED color change. PWM dimming is implemented in the LT3478 and LT3478-1 via the PWM pin. When the PWM pin is active high ( $T_{PWM(ON)}$ ) or low, the LED current is either at its maximum or off, respectively. The LED on time, and hence the average current, is controlled by the duty cycle of the PWM pin. Because the LED is always operating at the same current (maximum set by CTRL1), and only the average current changes, dimming is achieved without changing the color of the LED.

PWM dimming is not new, but the ability to achieve high PWM dimming ratios (requiring extremely low PWM duty cycles) is challenging. The LT3478 and LT3478-1 use a patented architecture to achieve PWM dimming ratios exceeding 3000:1 at 100Hz. The application circuit and waveforms shown



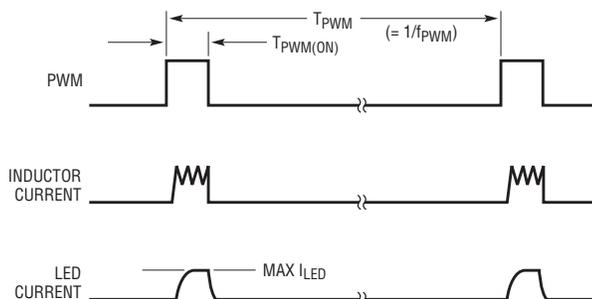
**Figure 7. CTRL1 and CTRL2 voltages vs temperature. The voltage at CTRL1 sets the maximum LED current until the voltage at CTRL2 falls below that of CTRL1. At that point (here at 25°C) CTRL2 takes over and derates the maximum current to rising temperature.**

in Figures 10, 11 and 12 show a PWM dimming ratio that can actually exceed 3000:1 if PWM on time is reduced to only 3 switching cycles ( $T_{PWM(ON)} < 3.3\mu s$  for  $f_{PWM} = 100Hz$ ).

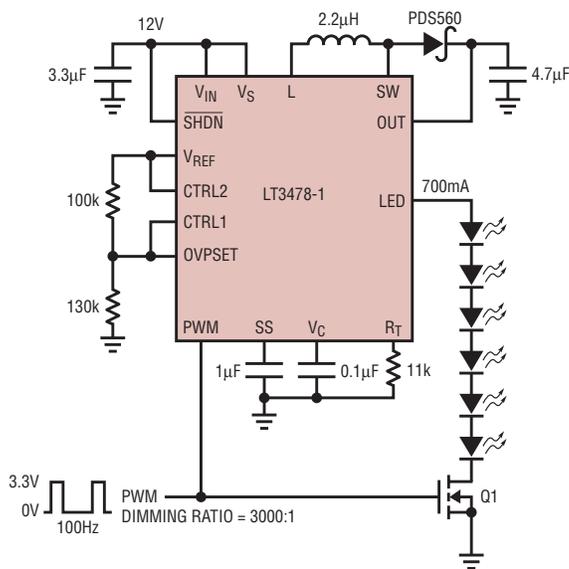
The simplified waveforms in Figure 10 and guidelines listed below explain the relationship between PWM duty cycle, PWM frequency, PWM dimming ratio and LED current. Strategies for achieving maximum possible PWM dimming using the PWM pin fall out of the relation:

$$\begin{aligned}
 \text{PWM DIMMING RATIO} &= \frac{1}{\text{MINIMUM PWM DUTY CYCLE}} \\
 &= \frac{1}{T_{PWM(ON)MIN} \cdot f_{PWM}}
 \end{aligned}$$

- ❑ For a PWM frequency ( $f_{PWM}$ ) of 100Hz, a PDR of 3000 implies a PWM on time of 3.3 $\mu s$ .
- ❑ The lower the PWM frequency, the greater the PWM dimming ratio (for a fixed PWM on time). However, there are limits to how

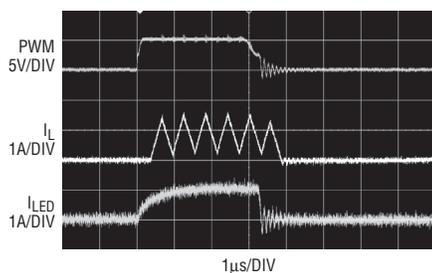


**Figure 9. PWM dimming waveforms**



**Figure 10. Boost LED driver optimized for high PWM dimming ratio (3000:1): 15W, 6 LEDs at 700mA**

- low the PWM frequency can be operated since the human eye can see flicker below about 80Hz.
- ❑ Higher programmed switching frequency ( $f_{OSC}$ ) improves PDR but reduces efficiency and increases internal heating. In general,  $T_{PWM(ON)MIN} = 3 \cdot 1/f_{OSC}$  (approximately 3 switch cycles).
  - ❑ Leakage currents from the output capacitor should be minimized. The LT3478 and LT3478-1 both turn off any circuitry running from  $V_{OUT}$  when the PWM pin is low.
  - ❑ For an even wider dimming range, the PWM and analog dimming features can be combined, where  $TDR = PDR \cdot ADR$  where  
 $TDR = \text{Total Dimming Ratio}$   
 $PDR = \text{PWM Dimming Ratio}$   
 $ADR = \text{Analog Dimming Ratio}$

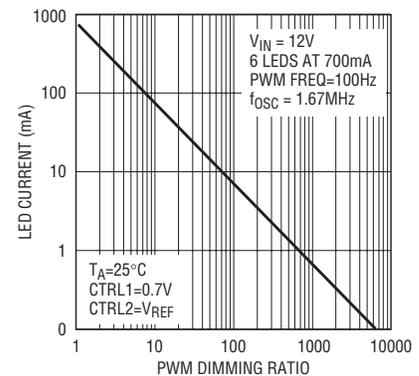


**Figure 12. PWM dimming waveforms for the circuit in Figure 10**

A PDR of 3000:1 and an ADR of 10:1 ( $CTRL = 0.1V$ ) yields a TDR of 30,000:1.

### Open LED Protection

The output voltage has a programmable maximum to avoid damaging the LEDs due to a disconnect (open LED) followed by a reconnect. During LED disconnect, the converter can go open loop and drive the output voltage so high that the internal power switch is damaged. Most LED drivers have a fixed maximum output voltage to save the switch, but this may be too high for the reconnected string of LEDs. The LT3478 and LT3478-1 provide a programmable overvoltage protection (OVP) level to limit output voltage based on the number of series connected LEDs. The OVPSET pin



**Figure 11. LED current versus PWM dimming ratio for the circuit in Figure 10**

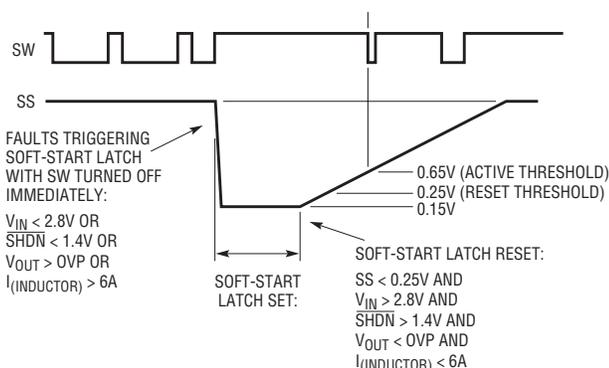
voltage limits the maximum output voltage, given by:

$$\text{Maximum output voltage} = OVPSET \cdot 41$$

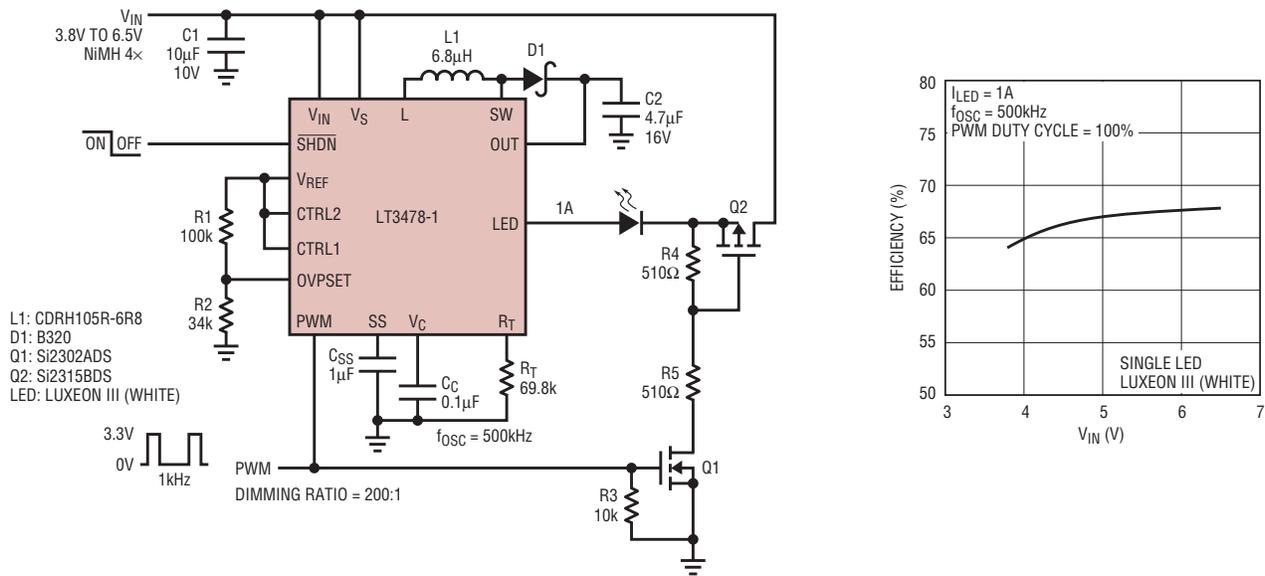
OVPSET voltage can be derived from  $V_{REF}$  by it's own resistor divider or by adding one resistor to the divider used to define CTRL1 voltage. OVPSET program level should not exceed 1V to ensure the switch voltage does not exceed 42V.

### Robust Operation: Fault Detection and Soft-Start

For robust performance during hot-plugging, startup, or during normal operation, the LT3478 and LT3478-1 monitor system parameters for any of the following faults:  $V_{IN} < 2.8V$ ,  $SHDN < 1.4V$ , inductor inrush current greater than 6A, and/or output voltage greater than programmed OVP. On detection of any of these faults, the LT3478 and LT3478-1 stop switching immediately and the soft-start pin is discharged (Figure 13). When all faults are removed and the SS pin has



**Figure 13. LT3478/ LT3478-1 fault detection and SS pin timing diagram**



been discharged to at least 0.25V, an internal 12µA supply charges the SS pin with a rate programmed using an external capacitor  $C_{SS}$ . A gradual ramp up of SS pin voltage is equivalent to a ramp up of switch current limit until SS exceeds the  $V_C$  pin voltage.

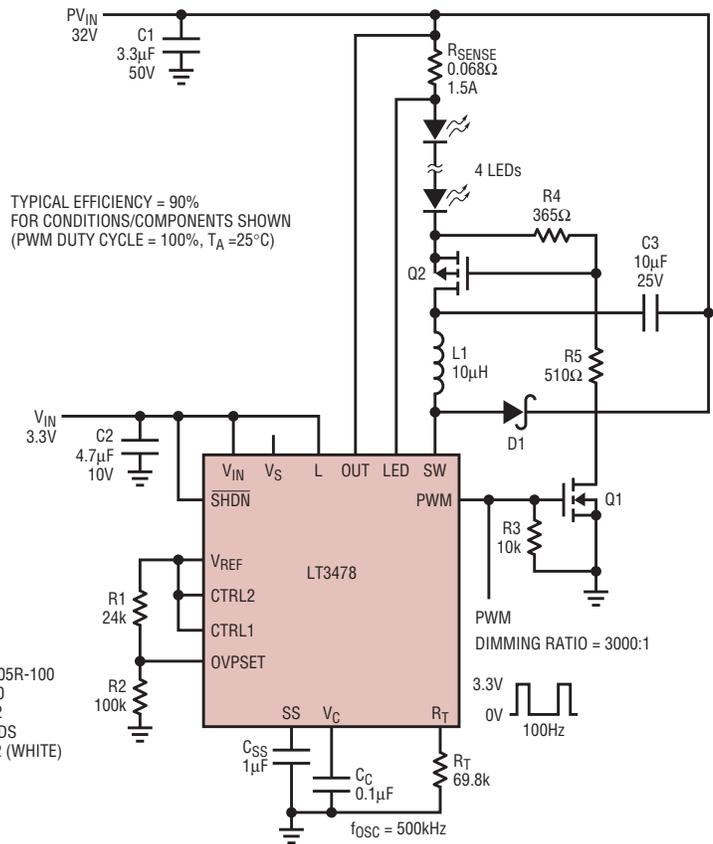
### High Efficiency: Separate Inductor and IC Supplies, Programmable $f_{osc}$ , 60mΩ Switch

The LT3478 and LT3478-1 can use separate supplies for the IC and the inductor to optimize efficiency and switch duty cycle range. Detection of inductor inrush current uses  $V_S$  and L pins independent of the  $V_{IN}$  supply of the IC (Figure 2). This allows  $V_{IN}$  to be supplied from the lowest available supply (at least 2.8V) in the system to minimize efficiency lost in the power switch driver. The inductor can then be powered from a supply (between 2.8V and 36V) better suited to the duty cycle and power requirements of the LED load. The switching frequency of the power switch can be tailored to achieve the optimum inductor size and efficiency performance required for the system. The 60mΩ switch further improves efficiency by keeping switch losses to a minimum for high duty cycle operation.

### Conclusion

The LT3478 and LT3478-1 are ideal for boost, buck or buck-boost mode LED applications requiring high LED current operation and high PWM dimming ratios. The high 4.5A peak switch cur-

rent limit combined with a new patent pending PWM dimming architecture allow the LT3478 and LT3478-1 to provide high PWM dimming ratios for LED currents up to 4A. 



# SAR ADCs Feature Speed, Low Power, Small Package Size and True Simultaneous Sampling

by Steve Logan and Atsushi Kawamoto

## Introduction

When it comes to quickly digitizing analog signals from a few hertz to a few megahertz, successive approximation register (SAR) ADCs are the best choice for a broad range of applications. Their fast response and low latency make SAR ADCs ideal for single channel or multichannel data acquisition.

Low power SAR ADCs are crucial as more designs migrate to lower supply voltages and tighter power budgets. Solution size is also a key requirement for designers needing a single snapshot of the input, as many low power SAR ADCs are used in portable or multichannel systems in which PCB space is limited. With designers trying to do more with less space, a small package becomes vital.

As package size shrinks, it makes sense to replace a parallel interface with a serial interface to reduce the number of data lines, which in turn reduces the size of both the SAR ADC and the microprocessor. Serial interfaces also reduce the headaches associated with routing many parallel data lines across a board. Linear Technology offers multiple families of fast SAR ADCs that combine speed, low

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power, small package size and simple serial interfaces.

## 6-Channel Simultaneous Sampling ADCs

Motor control is one of many applications that benefit from simultaneous sampling SAR ADCs. In motor control circuits, the phase relationship of measured channels must be preserved, thus requiring simultaneous sampling ADCs with multiple sample-and-hold

amplifiers (S/HA's). Data can be stored internally to be read out sequentially, with the phase relationship from the inputs intact. Without simultaneous sampling, control algorithms could incorrectly adjust the motor's torque or speed control, leading to vibrations and additional wear on the motor. Linear Technology has a growing family of low power simultaneous sampling ADCs that target motor control, servos, and general purpose AC power monitoring.

Linear Technology offers four low power, 6-channel simultaneous sampling ADCs, optimized for two fast sample rates (250ksps per channel and 100ksps) as well as two different resolutions (14 bits and 12 bits). All are pin- and software-compatible, making it easy to optimize designs for resolution, speed and cost. By using a 5mm x 5mm 32-pin QFN package, these ADCs achieve a solution size as much as six times smaller than comparable performance ADCs. A single 3V supply powers both the analog and digital circuitry, thus reducing power dissipation eliminating the need for higher voltage supplies.

**Table 1. Simultaneous sampling ADCs from Linear Technology**

Part Number	Resolution	Number of Channels	Sample Rate per channel	Power	Package	Input Voltage Range
LTC2351-14	14-Bit	6	250ksps	16.5mW	QFN-32 (5mm x 5mm)	±1.25V, 0V to 2.5V
LTC1408	14-Bit	6	100ksps	15mW	QFN-32 (5mm x 5mm)	±1.25V, 0V to 2.5V
LTC1407A	14-Bit	2	1.5Msps	14mW	MSOP-10	0V to 2.5V
LTC1407A-1	14-Bit	2	1.5Msps	14mW	MSOP-10	±1.25V
LTC2351-12	12-Bit	6	250ksps	16.5mW	QFN-32 (5mm x 5mm)	±1.25V, 0V to 2.5V
LTC1408-12	12-Bit	6	100ksps	15mW	QFN-32 (5mm x 5mm)	±1.25V, 0V to 2.5V
LTC1407	12-Bit	2	1.5Msps	14mW	MSOP-10	0V to 2.5V
LTC1407-1	12-Bit	2	1.5Msps	14mW	MSOP-10	±1.25V

### Low Power ADCs Optimized for 250ksps-750ksps

The 14-bit LTC2351-14 is a 1.5Msps, low power SAR ADC with six simultaneously sampled differential input channels. It operates from a single 3V supply and features six independent sample-and-hold amplifiers and a single ADC. The single ADC with multiple S/HA's enables excellent range match (1mV) between channels and channel-to-channel skew (200ps). The six channels can monitor two separate

motors, providing vital information about motor torque, speed, shaft position, and direction.

The versatile LTC2351-14 also suits other industrial monitoring applications such as 3-phase voltage monitoring to ensure line voltage compliance, 3-phase power monitoring of current and voltage, power factor correction, and data acquisition. These applications may require portability, and it is here that the LTC2351-14's low power and small size are most

desirable. Power consumption is a mere 16.5mW, which extends battery life. The 3-wire serial interface means fewer pins than traditional parallel output devices, allowing the LTC2351-14 to fit in a 32-pin, 5mm × 5mm QFN package.

When the LTC2351-14 is not converting, the ADC offers two power saving modes. Power dissipation can be reduced to 4.5mW in nap mode with the internal 2.5V reference remaining active. Sleep mode further reduces

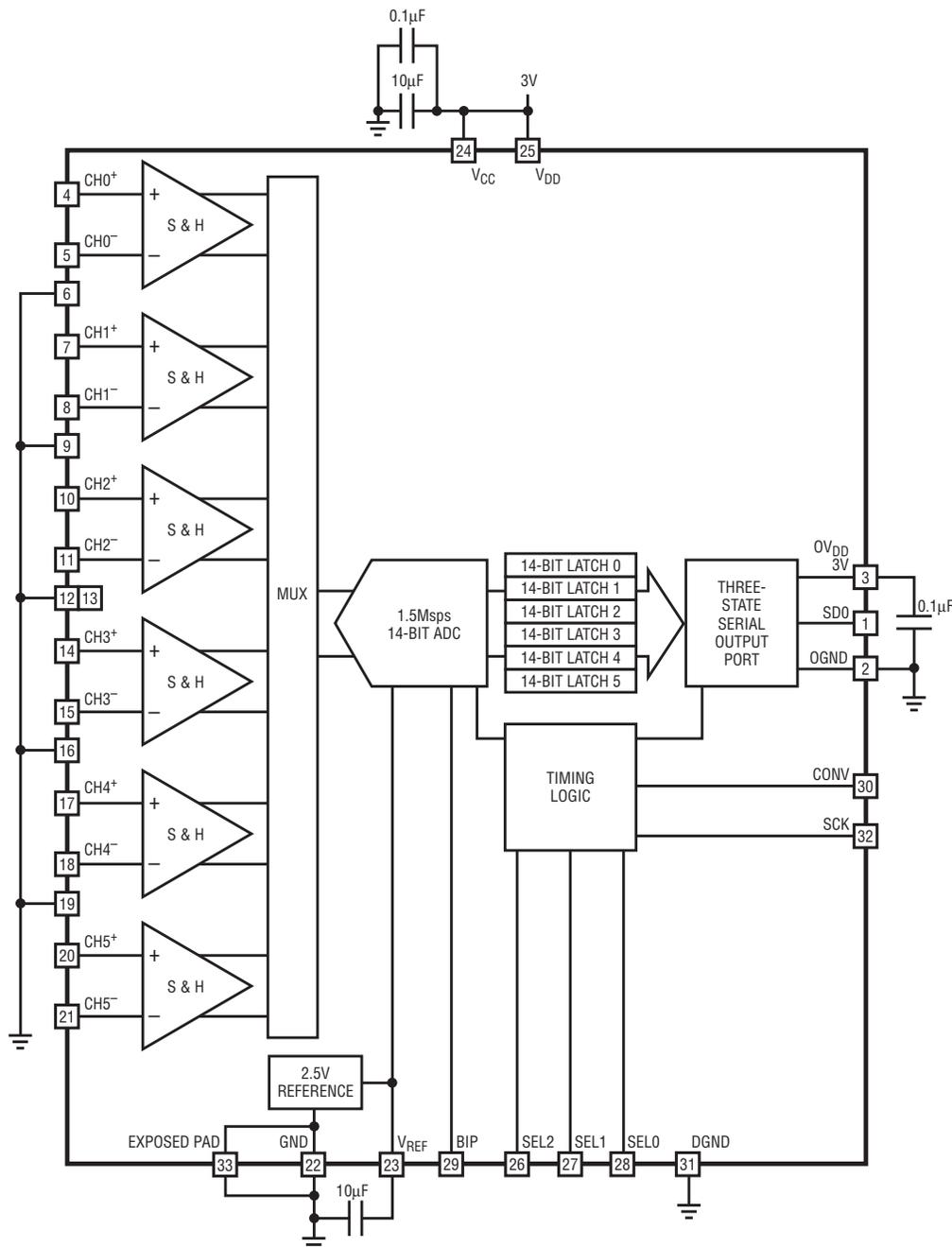


Figure 1. The LTC2351-14 includes six sample-and-hold amplifiers.

power consumption to 12 $\mu$ W, with all internal circuitry powered down, further extending battery life. Upon waking up from sleep mode, the internal reference settles within 2ms, and conversions resume thereafter within a single clock cycle.

Three input-select lines configure the number of differential inputs converted. Thus, higher speeds are possible as the number of channels converted decreases, from six differential inputs at 250ksps, two differential inputs at 750ksps, to one differential input at 1.5Mps. A bipolar/unipolar input line selects either a  $\pm 1.25$ V bipolar or a 0V to 2.5V unipolar input range. A 100kHz input signal yields a SINAD of 75dB and -90dB THD. The LTC2351-14's true differential inputs and 83dB common mode rejection make it ideal for minimizing common mode noise prevalent in harsh industrial environments. For lower resolution applications and performance-cost optimization, Linear Technology offers the pin- and software-compatible 12-bit LTC2351-12 ADC. The LTC2351-12 also simultaneously samples up to six differential channels, draws only 16.5mW of power and features 72dB SINAD.

Some simultaneous sampling ADCs are capable of measuring six channels, but use only two S/HA's, two ADCs, and two 3-to-1 multiplexers. In these competing ADCs, only two channels are simultaneously sampled. Multiple ADCs can mean mismatches from one

ADC to the other within the package. INL could be within the maximum ratings, but bow in one polarity on one ADC and the opposite polarity on the second ADC. By integrating six S/HA's and a single ADC, the LTC2351-14 does not suffer the anomalies associated with multiple ADCs and is ideal for applications that require simultaneously sampling more than two channels.

### Lower Sampling Rate ADCs with Improved AC Performance

Linear Technology also offers a second pair of 6-channel simultaneous sampling ADCs optimized for slower sampling rates. The 14-bit LTC1408 and 12-bit LTC1408-12 are optimized for output rates up to 100ksps/channel for all six channels, 300ksps for two channels, and 600ksps for one channel. The LTC1408 features improved AC performance (79dB SINAD at 300kHz, with an external reference). Like the LTC2351 family, both LTC1408 ADCs are low power (15mW), offered in a small 5mm  $\times$  5mm 32-pin QFN package, and include six sample-and-hold amplifiers. See Table 1 for a complete listing of these simultaneous sampling ADCs.

The LTC1408 and LTC2351-14 6-channel SAR ADCs are ideal for monitoring 3-phase voltages and currents, as shown in Figure 2. Attenuation networks externally reduce the voltage to within the selected bipolar/unipolar input ranges. While

three analog inputs measure the voltage, the other three channels use signal conditioning and filtering to convert the currents. The six S/HA's keep the phase relationship between the voltages and currents intact and data can be read out through the serial interface. These ADCs also include a digital output supply voltage that can be set between the analog supply voltage down to 1.8V, making it possible to interface with 1.8V, 2.5V or 3V digital logic.

### 2-Channel Simultaneous Sampling ADCs

For applications such as encoders and communications requiring simultaneous sampling on only two channels at rates greater than 1Mps per channel, fast SAR ADCs again work very well. Linear Technology offers a pin- and software-compatible family of 14-bit and 12-bit, 2-channel, simultaneous sampling SAR ADCs.

Like the 6-channel simultaneous sampling ADCs, the 14-bit, 2-channel LTC1407A-1 is also optimized for low power and small package size, further extending battery life and reducing total solution area. The LTC1407A-1 is available in a 10-pin MSOP package and dissipates only 14mW. This small ADC measures two  $\pm 1.25$ V bipolar channels simultaneously at 1.5Mps per channel or a single channel at 3Mps. No competing ADCs of similar size can meet the speed and input frequency range of the LTC1407A-1.

The pin- and software-compatible LTC1407A is a 0V to 2.5V unipolar 14-bit ADC. Both the unipolar and bipolar LTC1407 ADCs perform well when measuring differential AC inputs, making it a good choice for communications applications. The LTC1407A-1 and LTC1407A achieve 76.3dB SINAD and -86dB THD with a 750kHz input frequency and an external 3.3V reference. SFDR is 86dB and intermodulation distortion is -82dB at the same input frequency.

For applications requiring less resolution, the 12-bit LTC1407-1 (bipolar) and 12-bit LTC1407 (unipolar) ADCs are available. All four LTC1407 ADCs include a 2.5V internal reference, nap

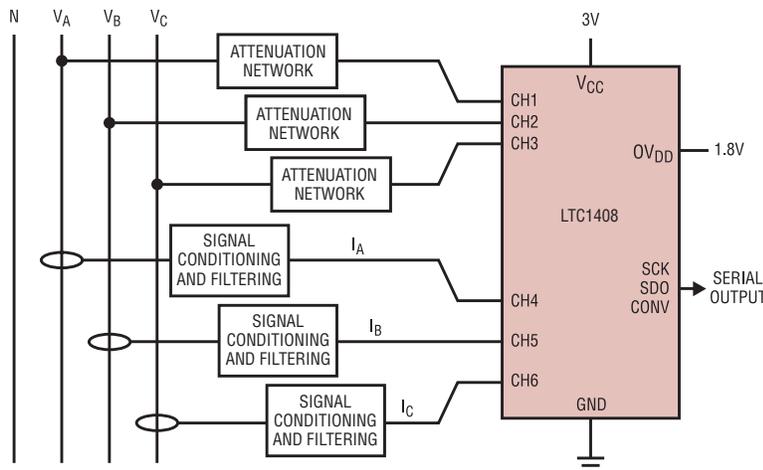


Figure 2. The LTC1408 is ideal for 3-phase power monitoring.

Table 2. Fast single-channel SAR ADCs from Linear Technology

Part Number	Resolution	Sample Rate	Package	Power	Input Voltage Range	I/O
LTC2355-14	14-Bit	3.5Msps	MSOP-10	18mW	0V to 2.5V	Serial
LTC2356-14	14-Bit	3.5Msps	MSOP-10	18mW	±1.25V	Serial
LTC1403A	14-Bit	2.8Msps	MSOP-10	14mW	0V to 2.5V	Serial
LTC1403A-1	14-Bit	2.8Msps	MSOP-10	14mW	±1.25V	Serial
LTC2355-12	12-Bit	3.5Msps	MSOP-10	18mW	0V to 2.5V	Serial
LTC2356-12	12-Bit	3.5Msps	MSOP-10	18mW	±1.25V	Serial
LTC1403	12-Bit	2.8Msps	MSOP-10	14mW	0V to 2.5V	Serial
LTC1403-1	12-Bit	2.8Msps	MSOP-10	14mW	±1.25V	Serial

(3.3mW) and sleep (6µW) power-down modes. Both families of 6-channel and 2-channel simultaneous sampling ADCs are detailed in Table 1.

### Data Acquisition Systems

SAR ADCs also excel in data acquisition applications due to the ability to multiplex multiple channels with little or no data latency. Data acquisition requires the ability to monitor a wide array of analog signals in industrial settings, often including temperature, pressure, voltage, or load currents. For example, an industrial control design may use thermocouples to monitor temperature variations, pressure sensors to measure physical changes, or chemical sensors to detect various environmental settings. Data acquisition could mean monitoring a single channel or hundreds of channels.

Figure 3 shows an example of the analog signal chain for a multichannel data acquisition system. After being routed through a series of multiplexers and signal conditioning circuits, these signals can be digitized by a fast single-channel SAR ADC, such as the LTC2355-14. With a fast SAR ADC, multiplexers and amplifiers with high gain bandwidths are used to switch through the various data inputs. The LTC1391 is an 8-to-1 multiplexer used to switch the various analog signals on the front end of the system. The LT6241 is a precision amplifier that has low noise (550nV<sub>P-P</sub>), 1pA bias current, 17MHz unity gain bandwidth, and provides a low impedance connection to the ADC.

### High Speed Single-Channel SAR ADCs

Along with its growing family of simultaneous sampling ADCs, Linear Technology is also adding to its family of pin- and software-compatible high speed single-channel SAR ADCs. The 14-bit, 3.5Msps LTC2356-14 mea-

sures a single differential input and communicates via an SPI-compatible serial interface. This SAR ADC operates from a single 3.3V supply, draws only 18mW at the maximum conversion rate, and is available in a tiny 10-pin MSOP package. The combination of high speed, low

*continued on page 38*

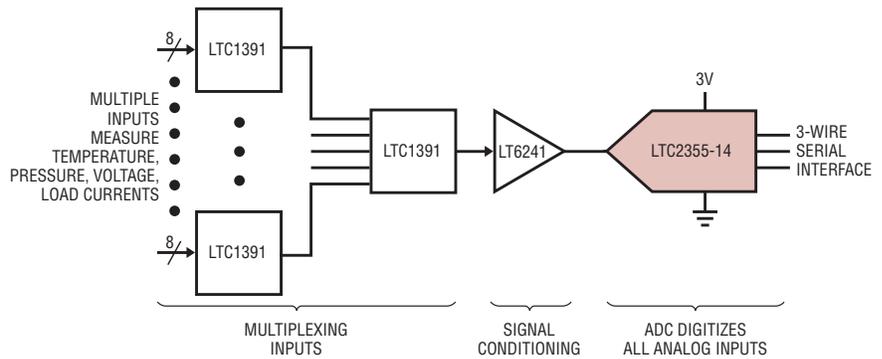


Figure 3. Industrial control data acquisition systems measure numerous signals with a single ADC.

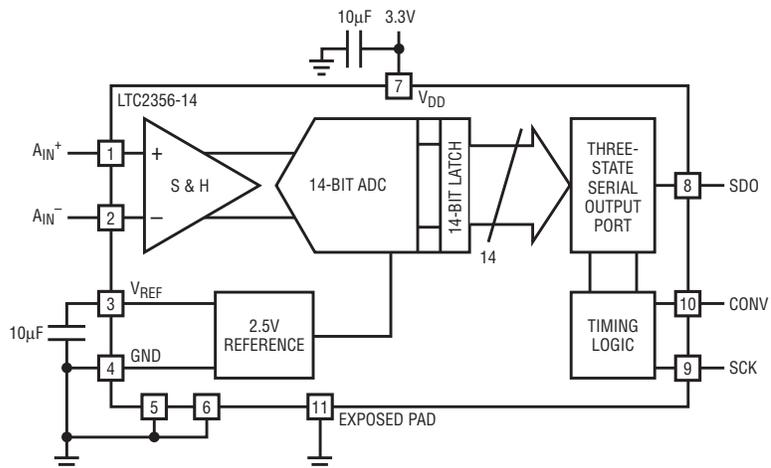


Figure 4. The LTC2356-14 single channel ADC is ideal for fast, low power applications.

# A Cool Circuit: 48V Ideal Diode-OR Reduces Heat Dissipation

by Dan Eddleman

## Introduction

High availability systems commonly demand redundant power supplies or backup battery feeds to enhance reliability. Traditionally, Schottky diodes were used to diode-OR these supplies at the point of load. However, as load currents climb, the forward voltage drop of the ORing diodes becomes a significant source of power loss. Designers are thus tasked with creating elaborate thermal layouts and heat sinks to contend with the diodes' rising temperatures.

A better solution for a high current, high availability system is to replace the Schottky diodes with MOSFET-based ideal diodes. This lowers the forward voltage drop of the diode-OR, shrinking thermal layouts and improving system power efficiency. The 4mm × 3mm LTC4355 simplifies the design of MOSFET ORing circuits by controlling two N-channel MOSFETs, which can combine supplies with voltages between 9V and 80V. The LTC4355 also provides the input voltage monitors, input fuse monitors, and forward voltage drop monitors frequently required in these systems.

## Operation

The LTC4355's basic operation is straightforward. It uses a linear amplifier and an internal charge pump to maintain a 25mV forward voltage drop across the external N-channel MOSFETs. The MOSFET sources are connected to the input supplies and the drains are joined at the output (Figure 1). When power is first applied, load current flows from the input supply with the higher voltage through the body diode of the MOSFET. The LTC4355 senses the voltage drop and enhances the MOSFET. For small load currents, the voltage across the MOSFET is limited to 25mV. Larger load currents cause the LTC4355 to fully enhance the MOSFET, resulting in a voltage drop of  $R_{DS(ON)} \cdot I_{LOAD}$ . The

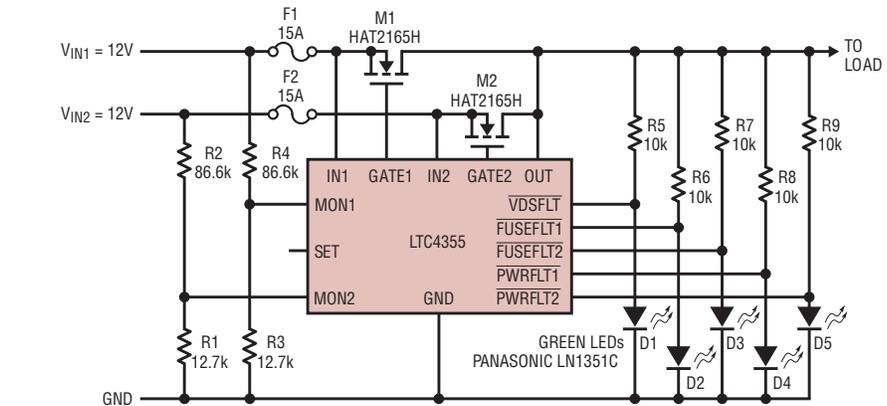


Figure 1. 12V/15A ideal diode-OR application

linear amplifier provides a smooth switchover between supplies without the oscillations, chatter, and reverse current common to comparator-based designs. If the higher input supply abruptly drops more than 25mV below the output voltage, as may occur during an input short circuit, the LTC4355 pulls the MOSFET gate low within about 0.5μs to limit the amount of reverse current that flows from the output back to the input.

## Fault Monitors

In addition to controlling the MOSFETs, the LTC4355 also performs several system health monitoring functions required in high availability systems. It detects when a fuse is blown, an input supply is low, or the forward voltage across a MOSFET is excessively large. If a fuse blows open, the  $\overline{FUSEFLT1}$  or  $\overline{FUSEFLT2}$  pin pulls low to signal which fuse has opened. Similarly, when an input supply is below its minimum voltage, configured by a resistive divider, the  $\overline{PWRFLT1}$  or  $\overline{PWRFLT2}$  pin pulls low to indicate which supply is out of regulation. The  $\overline{PWRFLT1}$  and  $\overline{PWRFLT2}$  pins also indicate when the forward voltage across a MOSFET exceeds a voltage programmed with the SET pin. Excessive forward voltage is a sign that a MOSFET may have failed or is conducting too much current. The LTC4355 in the DFN-14 package

provides a  $\overline{VDSFLT}$  pin, which also pulls low under this condition to allow the system to differentiate between a supply that is out of regulation and a MOSFET with too much forward voltage.

## 12V/15A Ideal Diode-OR

Figure 1 shows a simple 12V/15A ideal diode-OR application. An MBR1635 Schottky diode would dissipate 8W in this circuit. In contrast, the HAT2165 3.4mΩ MOSFET drops  $15A \cdot 3.4m\Omega = 51mV$  and dissipates only  $51mV \cdot 15A = 0.765W$ . The result is a drastic reduction in PCB area and heat sinking required to dissipate the power, not to mention a 4-point improvement in efficiency.

In this circuit, green LEDs indicate normal operation, and fault conditions cause the LEDs to turn off. Resistive dividers connected between the input supplies and the MON1 and MON2 pins configure the supply monitor thresholds near 10V. When a supply is below its minimum voltage, the respective  $\overline{PWRFLT1}$  or  $\overline{PWRFLT2}$  pin pulls low, thus turning off the D4 or D5 LED.

Likewise, the D2 or D3 green LED turns off to signal when a fuse has blown open. Under this condition, the IN1 or IN2 pin is pulled to ground by an internal 0.5mA pulldown current. As soon as the LTC4355 senses that

one of these pins is below 3.5V, it pulls the  $\overline{\text{FUSEFLT1}}$  or  $\overline{\text{FUSEFLT2}}$  pin low. Note that this condition also occurs when an input supply falls below 3.5V. Therefore, it may be necessary to confirm that  $\overline{\text{PWRFLT1}}$  or  $\overline{\text{PWRFLT2}}$  is high impedance, signaling a valid input supply voltage, before concluding that a fuse is blown open.

In Figure 1, the LTC4355 detects that a MOSFET has failed or is conducting excessive current by sensing the forward voltage drop across the MOSFET. The faults detected include a MOSFET that is open on the higher supply, excessive MOSFET current due to overcurrent on the load, or a shorted MOSFET on the lower supply. When one of these conditions occurs, the LTC4355 pulls the  $\overline{\text{VDSFLT}}$  pin (DFN-14 package only) and the  $\overline{\text{PWRFLT1}}$  or  $\overline{\text{PWRFLT2}}$  pin low to indicate which supply has the fault. The forward voltage threshold is configured at 1.5V by leaving the SET pin open. Tying the SET pin directly to ground

or through a 10k $\Omega$  resistor to ground configures this threshold at 0.25V or 0.5V, respectively. Note that during startup or when a switchover between supplies occurs, the  $\overline{\text{VDSFLT}}$  pin and the  $\overline{\text{PWRFLT1}}$  or  $\overline{\text{PWRFLT2}}$  pin may momentarily indicate that the forward voltage has exceeded the programmed threshold during the short interval when MOSFET gate ramps up and the body diode conducts.

### 48V/5.5A High Side and Low Side Ideal Diode-ORs

Many high availability systems require diodes on both the high and low side of the redundant power feeds. Combining the LTC4355 with the LTC4354 provides a complete solution for these applications. In the 48V/5.5A circuit of Figure 2, the LTC4355 and two FDS3672 MOSFETs perform the high side ORing function while the LTC4354 and two FDS3672s perform low side ORing.

At 5.5A, an MBR10100 Schottky Diode in a TO-220 package dissipates over 3W. The current passes through both a high side and a low side diode, resulting in a total power dissipation of over 6W. In contrast, an FDS3672 in a smaller SO-8 package dissipates 0.6W for a total of 1.2W. The ideal diode solution lowers the total power dissipation by 80%, reducing the necessary PCB area and heat sinking.

In the circuit in Figure 2, the LTC4355 and LTC4354 receive power when either input supply is present. The LTC4354's positive supply pin,  $V_{CC}$ , is regulated from the output of the LTC4355, always within a diode drop of the higher input voltage (+48VA or +48VB). At the low side, the LTC4355's negative supply pin, GND, connects to the output of the LTC4354, always within a diode drop of the more negative voltage (RTNA or RTNB). Consequently, both parts remain powered even when one of the supplies is disconnected or is out of regulation.

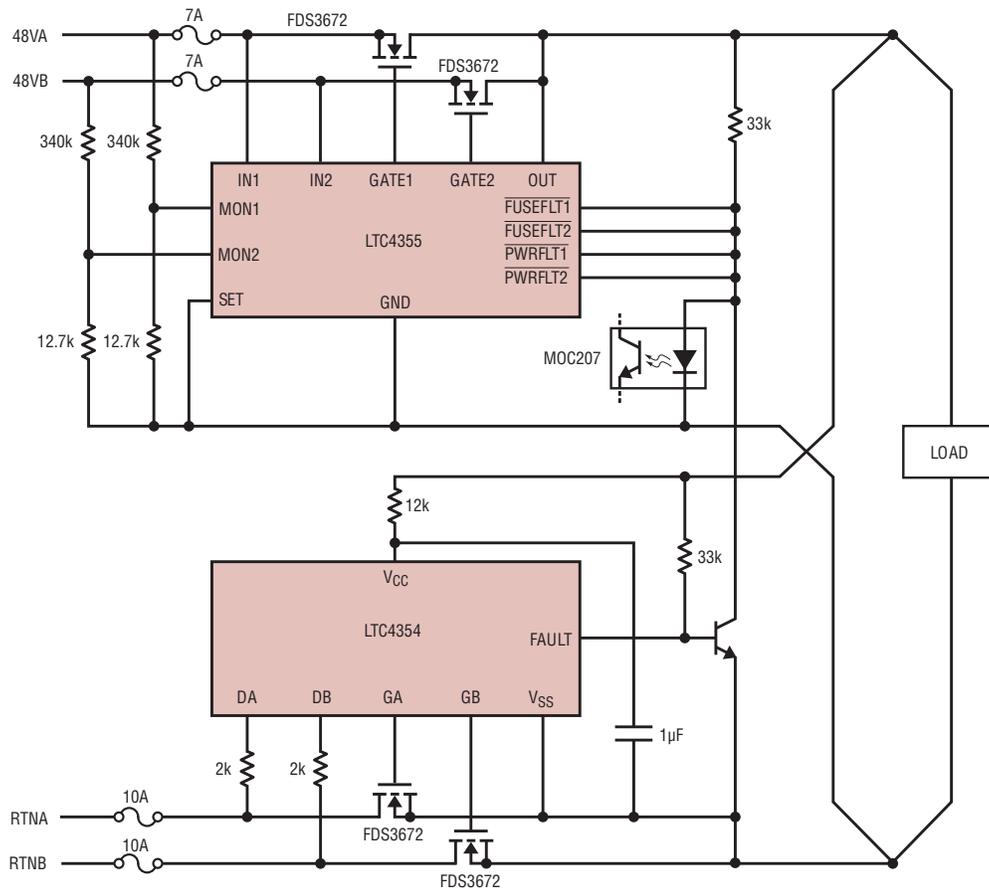
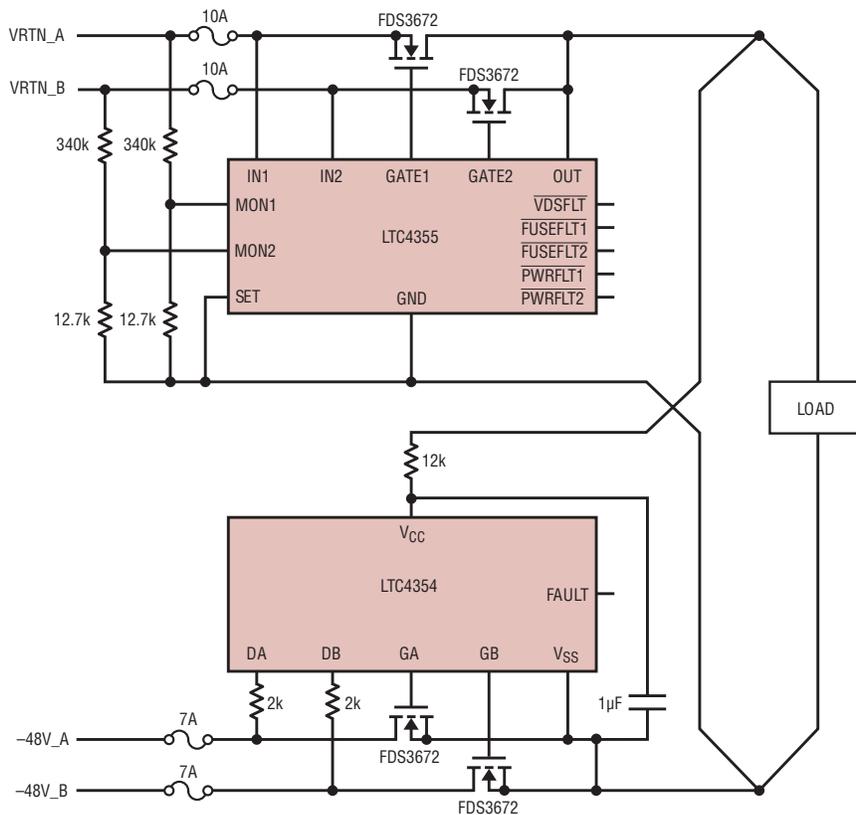


Figure 2. 48V/5.5A positive supply and negative supply diode-ORing with combined fault outputs.



**Figure 3. -48V/5.5A positive and negative supply diode-ORing for telecom systems.**

pin spacing sometimes desirable in higher voltage applications.

**-48V/5.5A High side and Low Side Diode-ORs for Telecom**

Many -48V telecom systems, including those that conform to the new AdvancedTCA specification, require ORing circuits on both the high and low side of the redundant power feeds. A few simple modifications convert the +48V solution in Figure 2 to the -48V solution in Figure 3. The +48V supply input becomes the return feed, VRTN, and the returns in the +48V system now serve as the -48V input feeds. The 10A and 7A fuses have been swapped, placing the 10A fuse in the high side return path. As a result, most fault conditions cause the high side 7A fuse to blow before the low side 10A fuse. Consequently, system potentials generally settle near VRTN after a fuse blows. The minimal circuit in Figure 3 does not connect the fault pins. If desired, faults can be monitored with a circuit similar to that in Figure 2.

**Conclusion**

The LTC4355 frees up PCB area by reducing power dissipation and the size of associated heat sinks in applications that require supply ORing. Its wide 9V to 80V supply operating range and 100V absolute maximum rating accommodate a broad range of input supply voltages with ample margin for supply variations and transients. In addition, the ability to provide system health monitoring functions makes it especially well suited to high-availability applications. Those systems that require both high side and low side ORing can combine the LTC4355 with the LTC4354 to form a complete solution. **LT**

Large supply variations and transients are easily accommodated by the wide operating voltage ranges of these two parts, 4.5V to 80V for the LTC4354 and 9V to 80V (100V absolute maximum) for the LTC4355.

This circuit combines all fault indicators to drive one optoisolator. If an input supply falls to less than 36V or the forward voltage drop across one of the positive-side MOSFETs exceeds 0.25V, the LTC4355's PWRFLT1 or PWRFLT2 pin pulls low to signal the fault. If a positive-side fuse blows open, the LTC4355 indicates a fault by pulling the FUSEFLT1 or FUSEFLT2 pin low. Finally, if the forward voltage across a low side MOSFET exceeds 0.26V, the LTC4354's FAULT pin drives an NPN that turns off the same

optoisolator driven by the LTC4355's pins.

Because the high side fuses have lower current ratings than the return fuses, the high side fuses blow first under most fault conditions. With the return fuses intact, system potentials tend to settle near ground after a fuse blows open.

The VDSFLT pin is not shown in this schematic. Since the PWRFLT1 or PWRFLT2 pin pulls low when the VDSFLT pin pulls low, VDSFLT is redundant in this application. Furthermore, this schematic is capable of accommodating not just the smaller DFN-14 package, but also the larger SO-16 package. While the SO-16 lacks a VDSFLT pin, it features the wider

reliability. A stable output is available with a wide range of output capacitors, including small ceramics. Internal protection circuitry in the LT3009 eliminates the need for external protection diodes, further saving space

and lowering cost. Competing devices can't come close to the performance and advantages that the LT3009 offers in the world of ultralow quiescent current regulators. **LT**

LT3009, continued from page 9

**Conclusion**

The LT3009 offers ultralow quiescent current, a shutdown mode, and wide input and output voltage ranges in tiny 2mm x 2mm DFN and SC70 packages without sacrificing performance or

# Highly Integrated USB Power Manager with Li-Ion Charger and Three Step-Down Switching Regulators in 4mm × 4mm QFN

by Amit Lele

## Introduction

Mobile technology has radically changed the way we acquire, share and disseminate information. Modern, feature-rich handheld and portable devices require several power management circuits, including a battery charger, multiple step-down switching regulators and low power LDOs for watchdog circuitry. If each of these functions is served by a separate power supply IC, each IC (and its external components) occupies valuable board space, consumes battery-draining quiescent current and significantly increases the overall development

and material costs of the device. The LTC3557 solves this problem by bringing all power management functions into a single device. It combines a full featured USB power manager, a Li-ion battery charger, three high frequency step-down switching regulators and a 3.3V always-on LDO in a single 4mm × 4mm QFN package.

## Features

The LTC3557 is a highly integrated power management and battery charger IC for single cell Li-Ion/Polymer battery applications. Table 1 high-

lights some of the key features of the LTC3557.

The LTC3557 can derive power from a current limited input such as USB. The programmable current limit is set by a single external resistor ( $R_{CLPROG}$ ) on the CLRPOG pin and the logic state of ILIM0 and ILIM1 pins. Table 2 shows the different operating modes of the input current limit.

The 1A (10x) mode is reserved for use with a higher current input power supply such as an AC wall adapter. Alternatively, power can be directly provided to the system load ( $V_{OUT}$ ) via an external PFET connected in

Table 1. Features of the LTC3557

Feature	Benefits
PowerPath Control	Allows seamless transition between input power sources (Li-Ion battery, USB, wall adapter or high voltage buck regulator) to supply system load.
WALL Input	Provides power from 5V wall adapter directly to system load through an external low impedance PFET
USB Input	Precision input current limit which communicates with the battery charger to ensure that input current never violates the USB specification
High Voltage Buck Control with Bat-Track™	Controls external HV buck to expand input voltage range up to 38V. The Bat-Track feature allows efficient charging of the battery to minimize heat dissipation in the application
Li-Ion Charger	Uses constant current/constant voltage architecture with thermal regulation for optimal charging. Preset float voltage accurate to 0.85%.
Temperature qualified charging using NTC	Disables charging of the battery under extreme temperature conditions outside a programmable range
Internal Safety Timer	Limits maximum charge cycle to 4 hours
$\overline{\text{CHRG}}$ Fault Reporting	Four modes of $\overline{\text{CHRG}}$ pin including ON, OFF, Slow Blink and Fast Blink to report various operating states
Three High Efficiency Step-Down Switching Regulators	High frequency switching (2.25MHz) stays out of the AM band and enables use of tiny inductors. Internally compensated to save valuable board space. User-programmable output voltages with external resistor divider. Power on Reset output for power sequencing.
Always on 3.3V LDO	Ultra low quiescent current 3.3V LDO for real time clock, standby power, pushbutton control, etc.

series with an AC wall adapter. The input supply range can be expanded by using an appropriate high voltage buck regulator as shown in Figure 1. The LTC3557 takes over the control of buck regulator via the  $V_C$  pin and sets the  $V_{OUT}$  pin voltage at a fixed offset above the battery voltage. This Bat-Track feature charges the battery at the highest efficiency. Absent all other input power sources, the battery provides power to the system ( $V_{OUT}$ ) through an internal  $200m\Omega$  ideal diode. An optional external  $<50m\Omega$  ideal diode can be used to minimize the voltage drop from BAT to  $V_{OUT}$  in high current applications.

The LTC3557 charger circuitry uses constant current/constant voltage architecture to optimize the charging of the battery. The battery charge current is set by an external resistor ( $R_{PROG}$ ) connected to the PROG pin as follows:

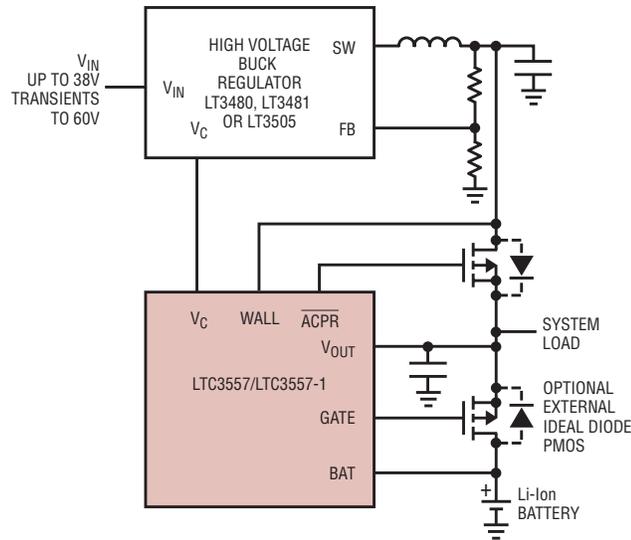
$$I_{CHG}(A) = \frac{1000V}{R_{PROG}}$$

The LTC3557 includes several safety mechanisms to handle situations when the available input current is less than the programmed charge current. This allows the system designer to set the charge current based on normal operating conditions rather than reducing the charging current to account for worst-case scenarios. These safety mechanisms are explained in more detail in the “Getting the Priorities Right” section below.

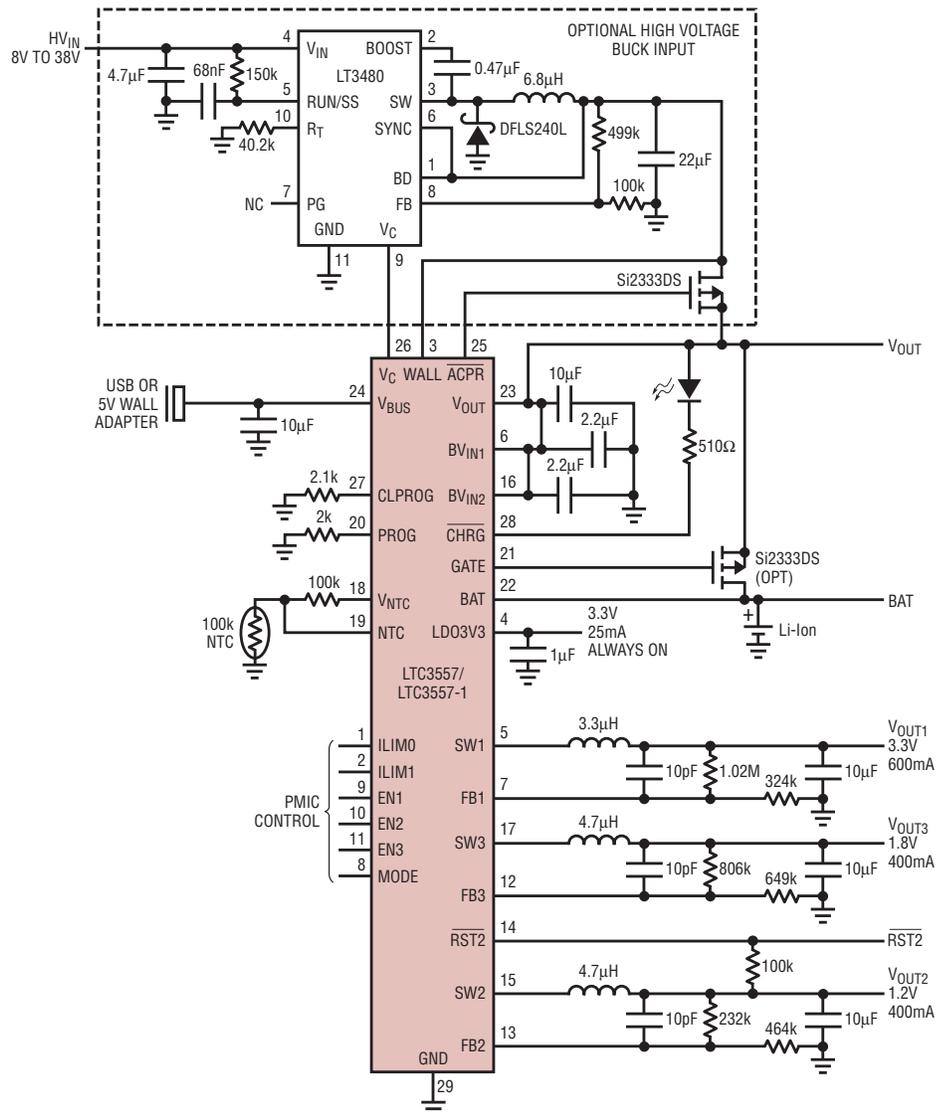
The LTC3557 includes three step-down switching regulators capable of delivering up to 600mA. Additionally, an always-on LDO with fixed 3.3V output voltage can deliver up to 25mA of load current. This can be used to power watchdog circuitry or other low power circuitry.

**A Typical Application**

Figure 2 shows a typical application using the LTC3557. In this configuration, the LTC3557 automatically switches between the high voltage buck power supply or the USB/5V wall adapter. The USB input current is programmed to nominal value of 476mA using a 2.1k resistor on the



**Figure 1. High voltage buck control using  $V_C$**



**Figure 2. Typical application circuit for LTC3557**

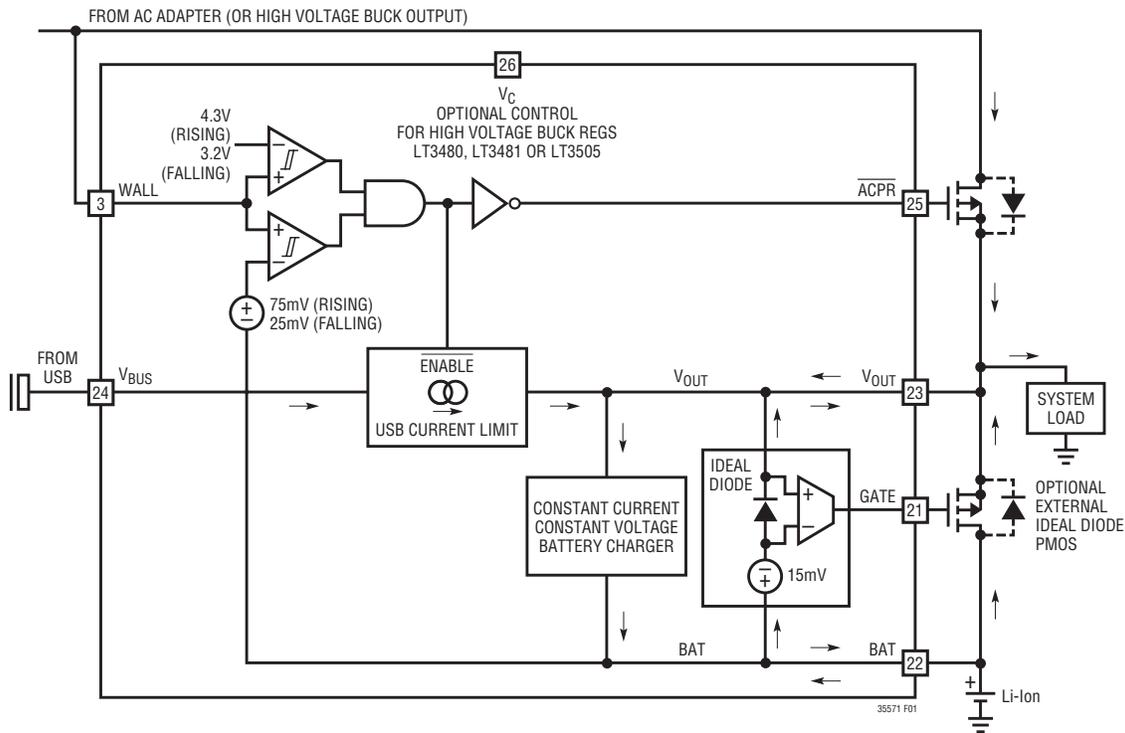


Figure 3. Simplified PowerPath block diagram

CLPROG pin. The charge current is programmed to 500mA using a 2k resistor on PROG pin. The resistor network on the NTC pin sets the battery charging temperature range from 0°C to 40°C based on R-T curve 1 characteristics for the 100k NTC thermistor. An LED on the  $\overline{\text{CHRG}}$  pin provides battery charging and status information.

V<sub>OUT1</sub> is set to 3.3V to drive higher power applications such as I/O or disk drives. V<sub>OUT3</sub> is set to 1.8V to drive medium power applications while V<sub>OUT2</sub> is set to 1.2V to drive a microprocessor core. The  $\overline{\text{RST2}}$  output can be used to provide power supply sequencing using the PMIC control pins. The optional external ideal diode can be used to provide a lower impedance path from BAT to V<sub>OUT</sub> for applications that draw heavy loads from the battery.

### Safety Timer and Automatic Recharge

An internal safety timer shuts off all charge current to the battery after 4 hours of charging. As long as the load current at V<sub>OUT</sub> does not exceed the current available from the external power source, the battery remains fully charged. If the load current at V<sub>OUT</sub> exceeds the current available from the external power source, the extra current is pulled from the battery. This

causes the battery to discharge and if the battery voltage drops below 100mV of its float voltage (4.2V for LTC3557 or 4.1V for LTC3557-1), an automatic recharge cycle is initiated.

### Getting the Priorities Right

The USB specification has very strict restrictions on the maximum current that can be pulled out of the bus. For this reason the LTC3557 provides load prioritization on the system load

Table 2. Controlled input current limit

ILIM1	ILIMO	I <sub>BUS</sub> (LIM)
0	0	100mA(1x)
0	1	1A(10x)
1	0	SUSPEND
1	1	500mA(5x)

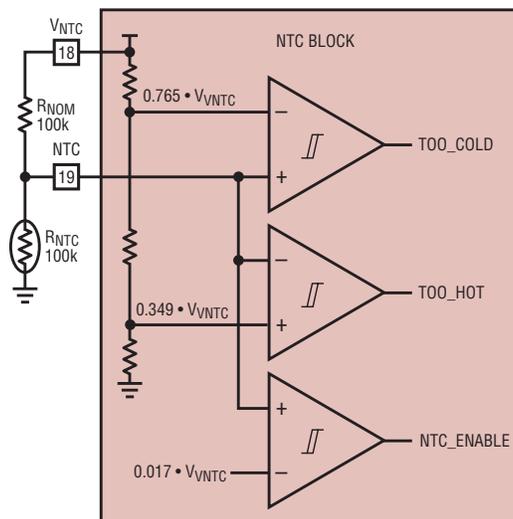


Figure 4. Temperature qualified charging using NTC

( $V_{OUT}$ ) as shown in Figure 3. Power is always prioritized at  $V_{OUT}$  and the battery charge current is automatically dialed back so that the USB current limit is never exceeded. This feature enables the battery charge current to be programmed to normal operating conditions rather than worst case load on  $V_{OUT}$ .

The charge current is also automatically dialed back at high temperatures to prevent the part from overheating. Additionally, if  $V_{OUT}$  starts to drop due to heavy load, the charge current is dialed back to maintain  $V_{OUT}$  near  $V_{BUS}$ . If the system load exceeds the programmed USB current limit, the additional current needed is drawn from the battery. Power provided directly to  $V_{OUT}$  pin via the WALL input is prioritized over USB power as USB power is current limited.

## Status Symbols

The  $\overline{CHRG}$  pin provides valuable information regarding the status of battery charging. The  $\overline{CHRG}$  pin is an open drain output that is pulled low during a normal charge cycle. When the charge current reduces to one tenth of the programmed value of charge current ( $C/10$ ) the  $\overline{CHRG}$  pin is let go and is pulled high by the external pull-up device to the appropriate rail voltage. Two Fault modes are also encoded on to the  $\overline{CHRG}$  output. If the battery voltage fails to rise above 2.85V even after charging it for a half hour, it is deemed to be a bad battery and this fault is reported at the  $\overline{CHRG}$  pin as a fast blink (6Hz signal modulated at 35kHz). Temperature qualified charging can be enabled with an external resistor divider on the  $V_{NTC}$  and NTC pins as shown in Figure 4. This defines

a range of temperatures for charging the battery and is a function of the thermal characteristics of the NTC resistor. When the battery temperature is outside the defined range, an NTC fault is indicated at the  $\overline{CHRG}$  pin by a slow blinking (1.5Hz signal modulated at 35kHz).

## Step-Down Switching Regulators

The LTC3557 includes three internally compensated 2.25MHz constant-frequency current-mode step-down switching regulators providing 600mA, 400mA and 400mA each. All step-down switching regulators can be programmed for a minimum output voltage of 0.8V and can be used to power a microcontroller core, microcontroller I/O, memory or other logic circuitry. Figure 5 shows the step-down switching regulator application circuit. The full-scale output voltage for each step-down switching regulator is programmed using a resistor divider as shown in the figure such that

$$V_{OUTx} = 0.8V \cdot \left( \frac{R1}{R2} + 1 \right)$$

Typical values of R1 are in the range of 40k $\Omega$  to 1M $\Omega$ . The capacitor  $C_{FB}$  cancels the pole created by the feedback resistors and the input capacitance of the FB pin, and also helps to improve transient response for output voltages much greater than 0.8V. A value of 10pF is recommended for  $C_{FB}$  for most applications.

All three of the step-down switching regulators support 100% duty cycle operation (low dropout mode) when the input voltage drops very close to the output voltage. Each regulator

can be individually enabled through its respective enable pin.

A single MODE pin sets the three voltage regulators in a high efficiency Burst Mode operation (MODE = 1) or low ripple pulse-skip mode (MODE = 0). For high enough load currents, in either mode, the step-down switching regulators automatically switch into constant frequency PWM mode operation. The high 2.25MHz switching frequency allows the use of tiny power inductors and stays out of the AM Band.

The step-down switching regulators also include soft-start to limit inrush current when powering on, short-circuit current protection and switch node slew rate limiting circuitry to reduce EMI radiation. It is recommended that the step-down switching regulator input supplies ( $V_{IN1}$  and  $V_{IN2}$ ) be connected to the system supply pin ( $V_{OUT}$ ). This allows the undervoltage lockout circuit on the  $V_{OUT}$  pin to disable the step-down switching regulators from operating outside the specified voltage range.

## Power Sequencing using $\overline{RST2}$

The  $\overline{RST2}$  open drain output responds to step-down switching regulator 2 and issues a Power ON reset signal 230ms after the feedback voltage (FB2) rises to within 8% of its final value. This output can be pulled to a desired voltage level using an external pull-up resistor and used for sequencing power rails. For example, it could be used to drive the enable inputs of the other switching regulators.

## Conclusion

In summary, the LTC3557 provides a highly integrated solution for handheld and mobile applications in a compact 4mm x 4mm QFN package. The variety of input power sources and externally programmable output voltages make it ideally suited for a broad range of applications. The feature rich Li-Ion charger provides protection against several real-world fault conditions while the versatile high frequency step-down switching regulators provide high efficiency power. 

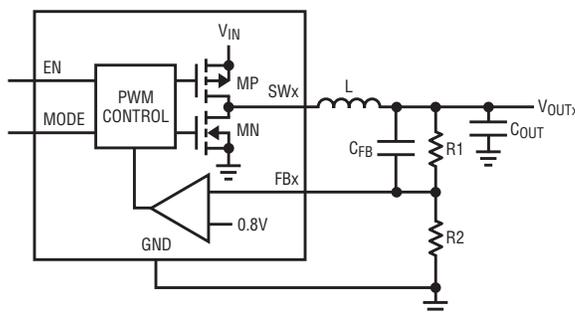


Figure 5. Buck converter application circuit

# Smart Battery Charger for Battery Backup

by Mark Gurries

## Introduction

The most common power source used for backup power is a battery. In a backup power system it is important to know if the battery is ready and reliable at all times by constantly monitoring its health and state of charge. Smart Batteries are currently the best available industry standard system that can satisfy these requirements.

Two important features of Smart Battery Systems (SBS) are that they are battery chemistry independent and provide a built-in gas gauge. Because the charging system no longer carries the burden of charge monitoring and applying chemistry-specific charge algorithms, the charger itself can be truly generic, accepting any Smart Battery, regardless of type or capacity. A host system needs to do nothing other than provide a Smart Battery charger to guarantee that a healthy battery is kept at full charge and a bad battery is detected.

This certainly simplifies charger design. The same charger can be used without modification in a variety of products. It also simplifies field and factory upgrades to different chemistries or higher capacities.

The LTC4100 Smart Battery charger is primarily targeted at big battery configurations in power hungry portable products, such as notebook computers. Many new products do not require the high voltage capability of the LTC4100, but still need all the advantages of a SBS system. The LTC4101 is a special version of the LTC4100 Smart Battery charger that is optimized to work with battery voltages below 5.5V, while retaining the space saving advantages of the LTC4100.

## The LTC4101 Smart Battery Charger

The LTC4101 is a compact Smart Battery charger optimized for battery voltages below 5.5V. It shrinks overall circuit size by reducing the size of external components. For instance, it takes advantage of the compact ceramic capacitors' space saving features while avoiding any audible noise. It also operates at a high 300kHz switching frequency, which allows the use of a very small, low cost inductor. Inductor values can be as low as 4μH at 4A with 7.5V of input.

The LTC4101 is a Level 2 (slave) Smart Battery charger that is compliant with both Smart Battery charger V1.1 and SMBus V1.1 standards. Input voltage range is 6V to 28V while the output charge voltage range is from 3V to 5.5V. A 10-bit current DAC and an 11-bit voltage DAC, with current accuracy of 5% and voltage accuracy of 0.8%, respectively, provide precision charge capabilities. A topside P-channel MOSFET allows 98% maximum duty cycle, dramatically reducing total part count and IC pin count while maintaining efficiency greater than 95% (see Figure 2).

The LTC4101 also offers many unique features, including a current limit and voltage limit system that prevents SMBus data corruption errors from generating harmful charge values. A patented SMBus accelerator<sup>1</sup> increases data rates in high capacitance traces while preventing bus noise from corrupting data (see Figure 3).

Figure 1 shows a typical compact single battery charger. This circuit can charge batteries with up to 1A and switch continuously down to zero load current. The LTC4101 is capable of charging currents up to 4A. Other features include:

- ❑ an AC present signal with precision 3%-accurate user adjustable trip points
- ❑ a safety signal circuit that rejects false thermistor tripping due to ground bounce caused by the sudden presence of high charge currents
- ❑ a DC input FET diode circuit that prevents battery current from flowing backwards into the wall adapter or DC power source
- ❑ an ultrafast overvoltage comparator circuit that prevents voltage overshoot when the battery is suddenly removed or disconnects itself during charge.
- ❑ VLIM and ILIM settings that are used to protect the battery from excessive voltage or current conditions that could occur if there are data corruption errors in SMBus communication.
- ❑ an input current limit sensing circuit<sup>2</sup> that is used to limit charge current to prevent wall adapter overload as the system power increases.

## Ceramic Capacitors Reduce Size and Improve Reliability

One of the biggest space saving changes that has occurred in recent years is the use of high capacitance and volt-

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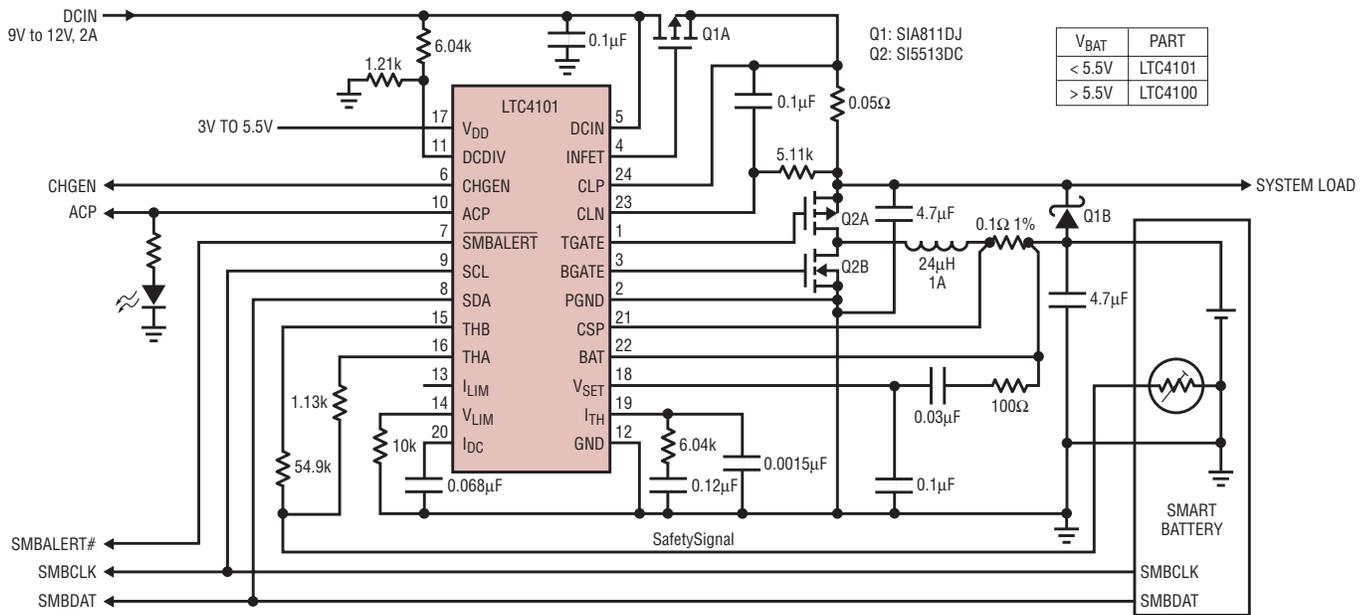
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**Figure 1. Charger with 2A input current limiting and 1A of charge power**

age (high C/V) ceramic capacitors. In switching regulator applications, the low ESR of ceramics allows them to handle a relatively large ripple current per microfarad while remaining relatively inexpensive. Battery chargers can reap the same benefits provided their feedback loops are stable with ceramic capacitors.

Ceramics come with their own unique challenges such as piezoelectric properties that can result in audible noise if there are AC currents with audible frequencies present. Such frequencies can occur in battery chargers at two load extremes: low dropout and light load.

Battery chargers run up against wall adapter voltages that are often

just a few volts above the peak battery voltage. Depending on the design, as the charger approaches 100% duty cycle, the switching frequency passes through the audible range on the way to DC. Alternatively, conditions where the charge current falls below the PWM controller's ability to maintain regulation can create discontinuous switching cycles or cycle-skipping. Cycle-skipping switching periods can occur in the audible range. This typically happens when batteries momentarily disconnect themselves during the charge process for termination condition evaluation, thus forcing the charge current to zero. Ceramic capacitors translate cycle skipping or low dropout switching activity into audible noise. The LTC4101 avoids this problem by switching continuously under all loads, even 0A.

**High Switching Frequencies Keep Inductors Small**

Charger system designers are often driven to reduce inductance values to take advantage of smaller form factor components. The problem is that less inductance for a given switching frequency results in more inductor ripple current, which increases the output capacitor size. However, if one

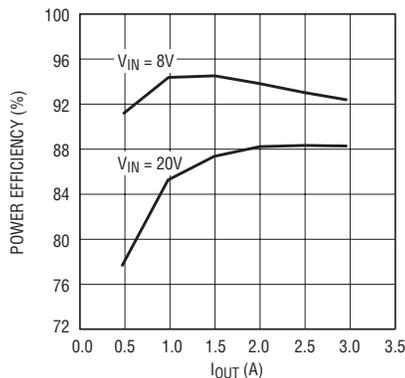
increases the switching frequency proportional to the reduction in inductance, the output capacitance can remain the same. The LTC4101 operates at a switching frequency of 300kHz, allowing tiny, low profile inductors to be used.

**Conclusion**

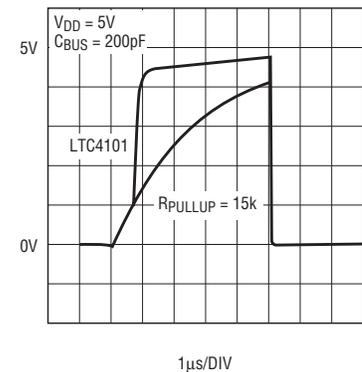
The LTC4101 Smart Battery retains all the same compact form factor advantages of the LTC4100 while being optimized for low voltage battery packs that can be found in compact products that require battery backup.

**Notes**

- 1. U.S. patent number 6650174
- 2. U.S. patent number 5723970



**Figure 2. Efficiency at single-cell Li-ion voltages**



**Figure 3. Built-in SMBus accelerator improves rise time performance and noise margin**

# Tiny Comparator Fits Anywhere You Need Micropower Control Functions

by Alexi Sevastopoulos

## Introduction

It's rare that an IC offers such a simple solution to so many common problems that it instantly becomes a favorite building block in the system designer's toolset. The LT6703 micropower, low voltage comparator and reference does just that by squeezing a single micropower comparator and accurate reference into a tiny 2mm × 2mm DFN package. Although only one of its comparator inputs is accessible (the other is connected to a 400mV internal precision voltage reference) its size makes it easy to fit just about anywhere even on the most crowded circuit boards.

The LT6703 is a smaller and simpler version of its sibling, the LT6700 dual comparator and reference. Its open-collector output enables level shifting, while its Over-The-Top® capabilities allow the input voltage range to span from -0.3V to 18V with respect to ground, regardless of the supply voltage. The internal bandgap voltage reference has an output voltage of 400mV ±1.25% over its wide temperature range (-40 to 125°C). The LT6703-2 and LT6703-3 differ by the polarity of the available comparator input and runs on 6.5µA with a typical propagation delay of 25µs.

The LT6703-2 has an available inverting input while the LT6703-3 (Figure 1) has an available non-inverting input. The comparator has 6.5mV of built-in hysteresis to ensure stable operation. In the LT6703-3, this hysteresis level can be increased using positive feedback circuitry. The threshold voltage, which represents the combined reference accuracy and comparator offset, is guaranteed at ±1.25% at 25°C. This threshold accuracy, in addition to the built-in 6.5mV of hysteresis, provides a clean switching threshold that the user can rely on even with slow varying inputs. For extra protection and to help elimi-

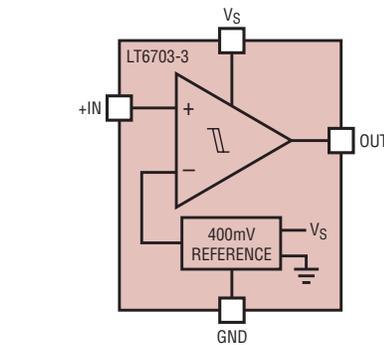


Figure 1. Block diagram of tiny 2mm × 2mm 1.4V-to-18V comparator

nate false triggering, a supply bypass capacitor should be added to prevent power supply glitches from disturbing the reference voltage.

## Features for Versatility and Ease of Use

### Wide Supply Range

The unique supply range of the LT6703 enables it to meet the standards of many industrial or battery-operated applications. In industrial applications where voltages above 5.5V are typically used, the LT6703 has no problem since its supply stretches up to 18V. Likewise, in battery-powered applications the supply reaches as

far down as 1.4V. This ability to run from a low voltage, combined with a low 6.5µA supply current, make the LT6703 ideal for low voltage system monitoring (shown in Figure 2).

As shown in Figure 2, the LT6703-3 can be run from a power supply rail or from a battery. In this system monitoring application, the output of the comparator goes low whenever the supply drops below the 3V threshold voltage—indicating that the system is running low on batteries or that there was a power failure or brown-out.

Although the LT6703 is specified as having ±10nA of input bias current, large input resistors are recommended to reduce overall supply current as shown in Figure 2. However, if the two input resistors are increased by a factor of ten, the input bias current of the comparator begins to affect the threshold value. With these larger input resistors and a supply voltage of 3V, the current through the input resistors is 260nA. With an input bias current of ±10nA, the comparator now sinks a significant portion of the supply current required to set the threshold voltage at the comparator input. As a result, an increase in supply voltage of a few hundred millivolts is required in compensation to reach the 400mV trip point. However, with the values shown in Figure 2, the current through the two input resistors is 2.6µA at the trip point, which considerably outweighs the comparator bias current and thus produces a reliable threshold voltage.

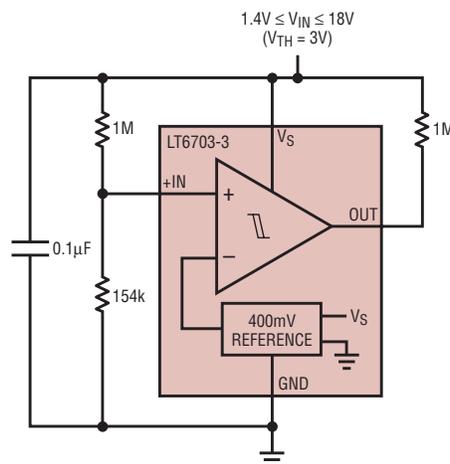
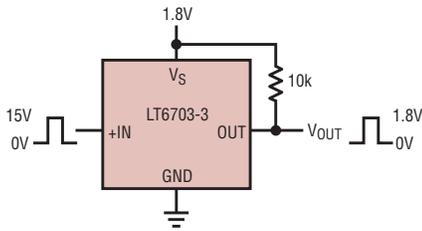


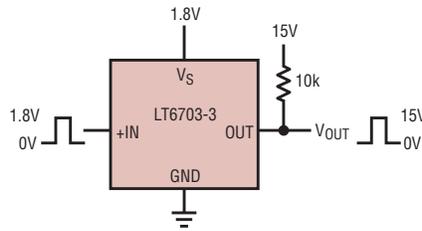
Figure 2. Micropower supply voltage monitor

### Over-The-Top Input and Open-Collector Output

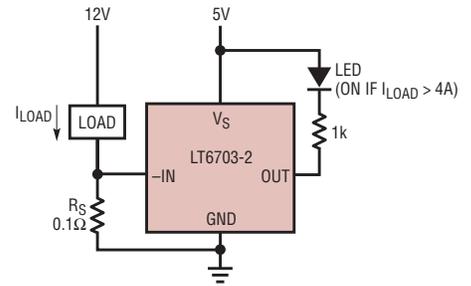
The LT6703 features Over-The-Top operation, which allows inputs with amplitudes as high as 18V, regardless of the supply voltage. In other words, operation at a low supply does not limit the input level. This feature,



**Figure 3. Simple level translator for shifting high voltages to low voltages**



**Figure 4. Simple level translator for shifting low voltages to high voltages**



**Figure 5. Low side current sense alarm**

along with the part's wide supply range, is especially useful in portable battery-powered applications, allowing a flexibility in input and supply voltage ranges that cannot be found in competing devices.

The comparator's open collector output also provides great flexibility. This allows the device to be used as a level translator since the output can be pulled up to 18V regardless of the supply voltage (Figures 3 and 4). In Figure 3, the LT6703-3 takes a 15V pulse input and translates it to a 1.8V output, all while running on a 1.8V supply. A simple modification reverses the translation as shown in Figure 4.

The use of multiple LT6703's also permits logical wire-AND implementation and can drive relatively heavy loads (up to 40mA) such as relays or LED indicators.

**Overload Protection**

The LT6703 can also be used to trigger an alarm dependent upon the amount of load current through an external sense resistor. In Figure 5, an LED is used on the output as an alarm signal. If the load current exceeds 4A, the sense resistor voltage rises above the 400mV threshold, triggering a state change on the output of the comparator. The internal NPN transistor at the output of the comparator now allows current to flow through it to ground, lighting up the LED and letting the user know that there is excessive current being conducted through the load.

In Figure 6, the load is protected by more than just an LED warning indicator. Once current through the load has exceeded the set limit and the voltage across the sense resistor rises

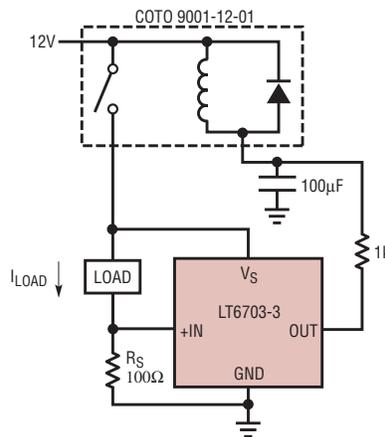
above the 400mV threshold voltage, a relay is tripped, cutting off the supply. Current conduction through the load is prevented as well. The output of the comparator remains high until the power supply is cycled back on and the load current decreases to below 4mA. When the output of the comparator is low, the part is capable of sinking up to 40mA from the supply through the relay although in this case it will only sink 6mA.

The 100μF capacitor shown in Figure 6 is responsible for pulling current through the relay coil. The large value is important because it allows enough time for the relay's internal switch to close and kick-start the circuit. The response time between the relay trip and supply reset is 40μs, regardless of the capacitor value. Figure 7 shows a modification to the circuit, allowing the circuit to restart without cycling the power supply. The auto-restart loop monitors the current through the load. The 1μF capacitor in the loop ensures that the supply of the

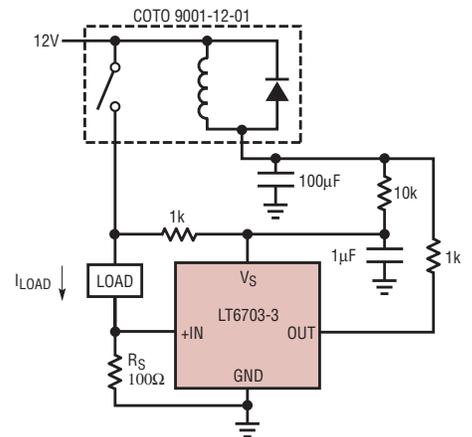
comparator does not turn back on when the output goes high. As the load current is decreased, the supply voltage gradually increases. When it hits 1.4V, the output goes low and the relay switch closes, turning the circuit back on.

**Conclusion**

Linear Technology continues to innovate by crafting the LT6703 series of precision, micropower comparators in a tiny 2mm × 2mm DFN package. These products provide an excellent solution to many design challenges for threshold detection applications, with characteristics accommodating wide temperature spans and space-critical designs. Its unique Over-The-Top® feature offers versatility and performance ideal for portable, battery-powered commercial products as well as industrial or high-temperature grade system monitoring applications. The LT6703 excels in all specifications that set system performance.



**Figure 6. Latch-off protection circuit**



**Figure 7. Latch-off protection circuit with load sensing auto-reset**

# 3-in-1 Device Replaces Battery Charger, Overvoltage Protection and PowerPath Manager for USB/Battery Powered Devices

by Andy Bishop

## Introduction

An efficient Li-Ion battery powered system requires at least three distinct circuits to control the power path between the load, the battery and the power source (see Figure 1). The minimal circuit requirements include:

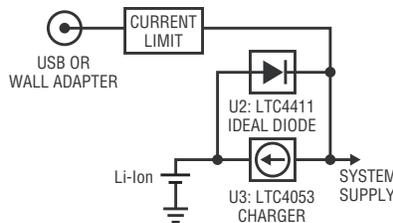
- ❑ a battery charger,
- ❑ a power switch to select powering the load from either the battery or the wall adapter (when present),
- ❑ and a current regulator for the wall adapter/USB input.

This, of course, assumes that the load draws power from a communal power bus, as opposed to attaching directly and exclusively to the battery. A direct-to-battery topology might be simpler, precluding the need for the power path controller and regulator, but it is far less efficient and significantly more restrictive. For instance, if the battery is fully drained, no power can be delivered to the load, even if wall adapter power is available.

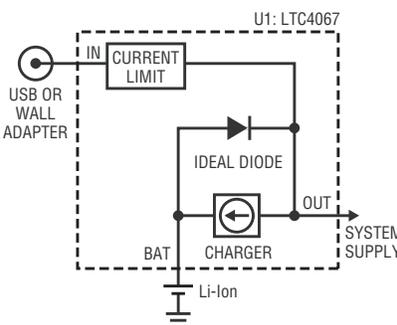
The LTC4067 Li-Ion charger and PowerPath™ controller combines the efficiency, flexibility and robust nature of a 3-chip solution with the simplicity of a direct-to-battery topology by replacing three components with a single device, as shown in Figure 2. The LTC4067's advanced topology battery charger optimizes power utilization while limiting input current to a programmable level, making it ideal for USB powered applications.

## Working with USB Port Current Limits

In applications where input current consumption is constrained, the LTC4067 is able to satisfy USB power requirements. Take the example of a portable device with a disk drive that draws power from either a battery or



**Figure 1. Battery charger current-limit and ideal diode supply connections with intermediate voltage bus.**



**Figure 2. Intermediate voltage bus supply connections with the LTC4067**

the USB. Peak current consumption may readily exceed USB limits when the disk is spinning up. In this situation, the LTC4067 optimizes power management by sharing the load between the battery and the USB, while limiting the current from the USB port. When load current decreases, the LTC4067 automatically switches over to charge the battery with any excess USB current that is not consumed by the load.

The LTC4067's input current limit is programmable via a resistor at the CLPROG pin. Control inputs ILIM0 and ILIM1 are used to set USB high power, low power or suspend operating modes—or allow for much larger current limit when powering from a wall adapter. The LTC4067 also provides instantaneous USB current and

charge current monitoring, allowing the application to perform advanced gas-gauge functions.

## Working with Unregulated Wall Adapters

With the addition of an external high-voltage PFET, the LTC4067 provides an automatic overvoltage protection function that allows the LTC4067 to automatically disconnect itself in the event that the wrong wall adapter is applied.

Figure 3 illustrates an application where the LTC4067 charges a single-cell Li-Ion battery from a 1A wall adapter. The overvoltage protection circuit includes the OVI and OVP pins of the LTC4067 and an external PFET in series with the IN pin. The PFET serves to disconnect the LTC4067 from potentially damaging overvoltage conditions. When the OVI input senses a voltage greater than 6V, the OVP output pulls up to disable the PFET. When OVI falls below this threshold, the OVP output falls low, turning on this PFET. Note that the body diode of this PFET is connected so that it does not forward bias when an overvoltage condition exists. While the overvoltage condition persists, the input power path is disabled, but system power is provided by the battery. A 10nF capacitor placed from OVI to OVP ensures that the PFET is quickly disabled in the event that fast edges occur when the wall adapter is suddenly hot-plugged. An optional, low power Zener diode is also recommended in the event that voltage surges occur after the device is powered.

In the example of Figure 3, the input current limit from the wall adapter is programmed to 1A with a 1k resistor



# Universal 12-Output LED Driver Controls 4-RGB LEDs

By Ted Henderson

## Introduction

RGB LEDs produce a wide range of colors, including white, making them highly versatile. Each RGB LED requires three drivers, one for each color LED. Using a multiple output LED driver for RGB applications can save solution size and cost versus single LED drivers. The LTC3207 and LTC3207-1 each provide 12 individually programmable current sources (universal drivers). This allows them to drive up to 12 white LEDs or four RGB LEDs, as shown in Figure 1. Each universal LED driver is controlled by a dedicated 6-bit linear DAC that covers an LED output current range of 400 $\mu$ A to 28mA. Any unused universal or camera outputs can simply be connected to ground and left unprogrammed by the I<sup>2</sup>C port.

The LTC3207 and LTC3207-1 include all of the functions required to drive 12 LEDs and one camera LED, including the following features: a high power multimode charge pump with automatic mode reset, a precision internal current source and voltage reference to set full scale current, and 13 precision LED current source outputs each controlled by a DAC and an I<sup>2</sup>C data interface. Only five small external ceramic capacitors are required. The LTC3207 and LTC3207-1 are packaged in a small, low profile

4mm  $\times$  4mm 24-pin QFN plastic package and can operate over an input voltage range of 2.9V to 5.5V.

## Features

### Automatic Blinking and Gradation Reduce I<sup>2</sup>C Bus Traffic

The LTC3207 and LTC3207-1 have incorporated features that greatly reduce I<sup>2</sup>C bus traffic. The universal LED outputs can be programmed to blink at rates up to 2.5 seconds independent of direct I<sup>2</sup>C control. Gradation times from 0.25s to 1s can be programmed to smoothly ramp the brightness of any channel from off to the programmed current and down to zero independent of the I<sup>2</sup>C port.

An ENU pin is also available to directly enable the universal drivers independent of the I<sup>2</sup>C port once the device has been programmed. Each universal output can be individually programmed to gradate or blink. Each universal output can also be controlled by the ENU pin. *Application Note 108* (available on our web site at [www.linear.com](http://www.linear.com)) outlines recommended programming examples for all of these features.

### High Power Charge Pump

Both parts automatically change the charge pump mode to optimize ef-

ficiency. Initially the part starts in 1x mode. When a dropout is detected, indicating that the LED driver voltage is too low to maintain the programmed current, the charge pump changes modes to 1.5x (4.6V). A subsequent dropout changes the charge pump to 2x mode (5.1V). The charge pump is automatically reset to 1x mode whenever an I<sup>2</sup>C write occurs, gradating down has completed, a blink period has completed, a camera flash has completed, or when ENU goes low.

Soft-start at power up and between charge pump mode changes ensures low inrush currents. Slew rates on the flying capacitor pins C1M, C1P, C2M and C2P are controlled to minimize conducted and radiated noise. The charge pump can be forced to operate in 1x, 1.5x or 2x mode via the I<sup>2</sup>C port for applications where the charge pump is used to power external devices or when the supply voltage is high enough such that the charge pump is not required.

### Serial Port

The microcontroller-compatible I<sup>2</sup>C serial port provides all of the command and control inputs for the LTC3207 and LTC3207-1. There are 16 data register, one address register and one sub-address register. The maximum clock operating frequency is 400kHz. These parts are receive-only (slave) devices. Two I<sup>2</sup>C addresses are available by using either the LTC3207 or LTC3207-1.

### Conclusion

The small package and high level of integration of the LTC3207 and LTC3207-1 make these parts an excellent choice for a wide range of LED applications. The blinking and gradation features coupled with individual LED current control and simple LED disable features make these parts truly universal, extremely easy to use with minimal I<sup>2</sup>C bus traffic. 

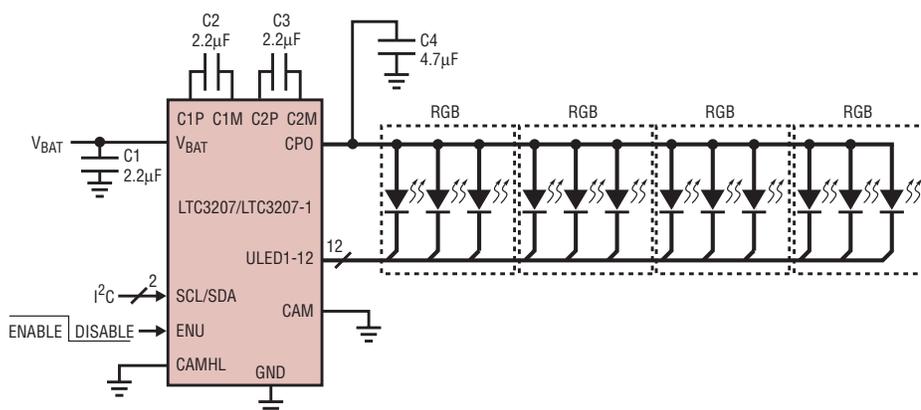


Figure 1. A four RGB LED driver

# 12A Monolithic Synchronous Buck Regulator Accepts Inputs up to 24V

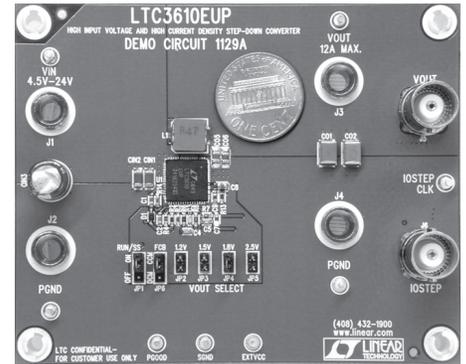
by Stephanie Dai and Theo Phillips

## Introduction

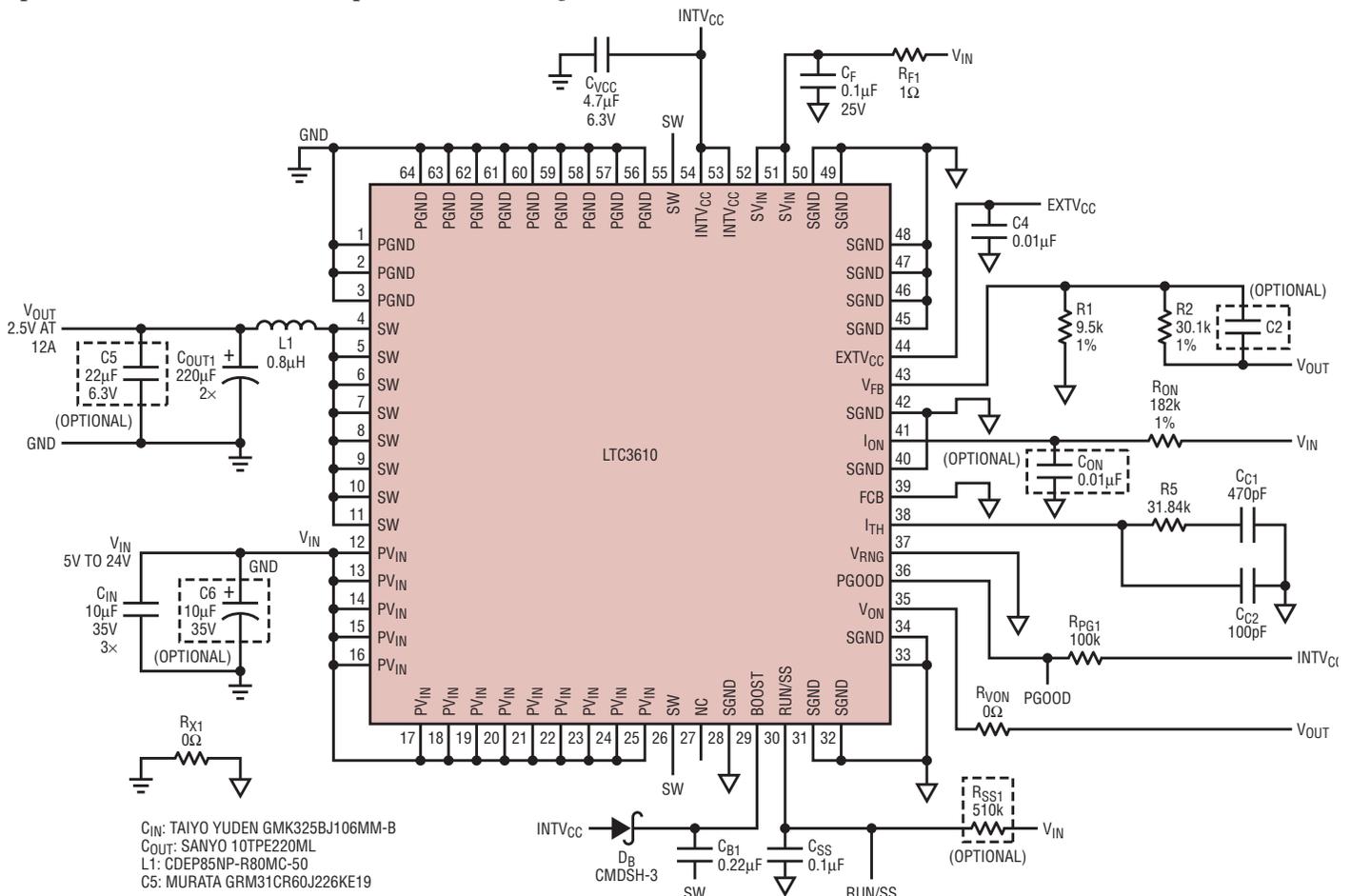
The LTC3610 is a high power monolithic synchronous buck regulator capable of providing up to 12A from inputs as high as 24V in a complete solution that takes little space (Figure 1). It integrates the step-down controller and power MOSFETs into a single, compact 9mm x 9mm QFN package. Its high step-down ratio, wide input and output voltage range and high current capability present a single IC solution for many applications previously requiring separate FETs and controller ICs. Its very low profile (0.9mm max) allows mounting on the back of a circuit board, freeing up valuable front-side board space.

## Flexible Control

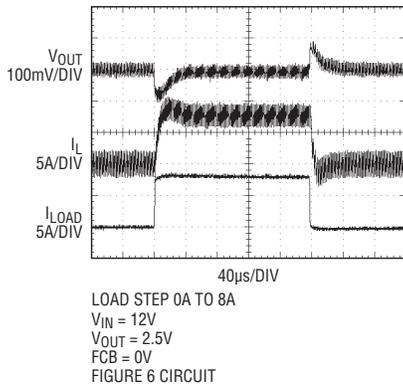
High step-down ratios (Figure 2) are possible because of the LTC3610's constant on-time operation and valley current control architecture, which allow a minimum on-time of less than 100ns. Output voltages approaching  $V_{IN}$  are also possible (Figure 5). In either case, efficiency is very high—up to 97% (Figures 4 and 6). Synchronous operation affords high efficiency at low duty cycles, whereas a non-synchronous converter would conduct current through the forward drop of a Schottky diode most of the time. Transient response (Figure 3) is fast because the LTC3610 reacts *immediately* to a load increase. It does



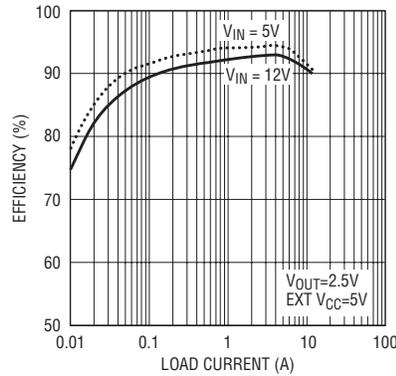
**Figure 1.** Who says a lot of space is needed for a complete high power density step-down regulator? The LTC3610 is capable of providing up to 12A from inputs as high as 28V. Its low 0.9mm profile allows it to be mounted on the back of the board too.



**Figure 2.** This converter runs at 550kHz and delivers 2.5V at 12A from an extremely wide 5V–24V input.



**Figure 3.** The LTC3610 responds quickly to an 8A transient (circuit of Figure 2).



**Figure 4.** Efficiency vs load current for the circuit of Figure 2

not wait for the beginning of the next clock cycle to respond, so there is no clock latency.

The LTC3610 can be programmed for two kinds of light-load operation: forced continuous mode or discontinuous mode. Forced continuous operation offers the lowest possible noise and output ripple. The top MOSFET turns on for the programmed on-time and the bottom MOSFET

turns on for the (remaining) off-time. Inductor current is allowed to reverse, even at no load.

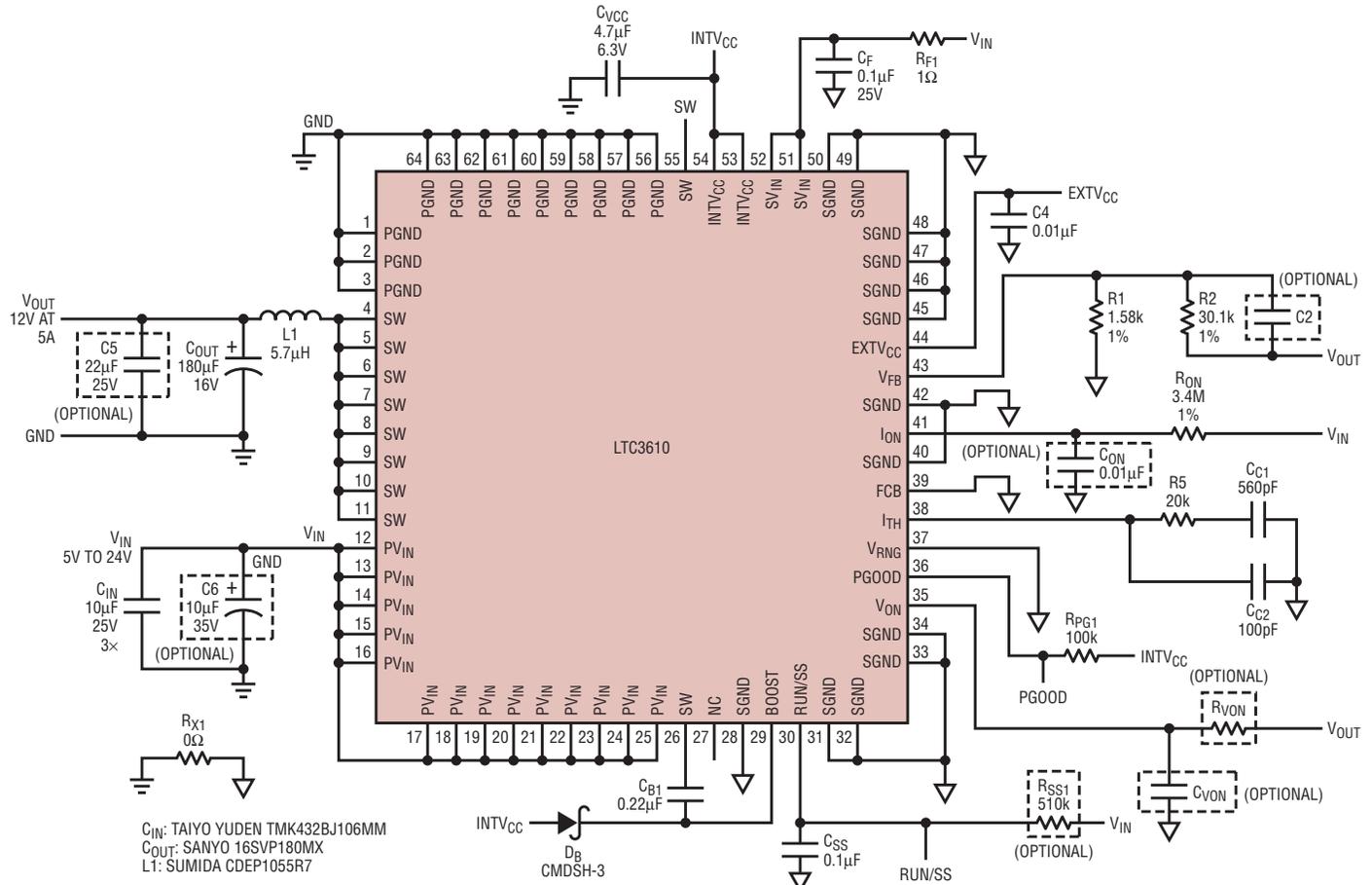
In discontinuous mode, the top MOSFET turns on for a preset on-time. Then (after a brief non-overlap period) the bottom MOSFET turns on until the current comparator senses reverse inductor current. When the error amplifier senses a small decrease at the feedback node  $V_{FB}$ , its output

(the  $I_{TH}$  pin) rises, initiating another cycle. As the load current rises, so does the average inductor current. Eventually, the interval between constant on-time pulses ends before the inductor current can reach zero, at which point the inductor continuously conducts current. This point is determined by duty cycle, inductance value, and the interval between constant on-time pulses. By using single on-time pulses of fixed width, this mode provides well-controlled output ripple at any supported load. This process also prevents reverse inductor current, which minimizes power loss at light loads.

The on-time is set by the current into the  $I_{ON}$  pin and the voltage at the  $V_{ON}$  pin according to a simple equation

$$T_{ON} = \frac{V_{VON}}{I_{ION} \cdot 10pF}$$

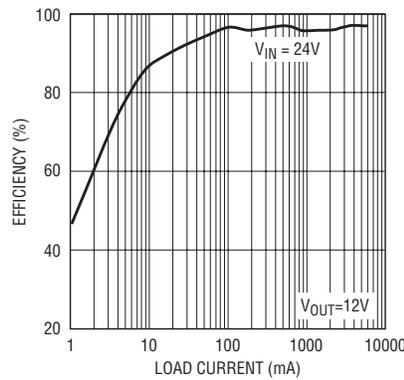
Tying a resistor  $R_{ON}$  from  $V_{IN}$  to the  $I_{ON}$  pin yields an on-time inversely proportional to  $V_{IN}$ .



**Figure 5.** Although the LTC3610 is optimized for high step-down ratios, it can also regulate output voltages beyond the range of many DC/DC buck converters. For example, this schematic shows a 500kHz regulator delivering 12V at up to 5A, with high efficiency and low output ripple.

Adjustable current limit is also built-in. The inductor current of LTC3610 is determined by measuring the voltage across the sense resistance between the PGND and SW pins, where  $R_{DS(ON)}$  of the bottom MOSFET is about 6.5m $\Omega$ . The current limit is set by applying a voltage to the  $V_{RNG}$  pin, which sets the relative maximum voltage across the sense resistance. An external resistive divider from the internal bias, INTVCC, can be used to set the voltage of the  $V_{RNG}$  pin between 0.5V and 1V resulting in a typical current limit of 16A to 19A. Tying  $V_{RNG}$  to SGND defaults the current limit to 19A.

The LTC3610 also has soft-start and latch off functions enabled by the Run/SS pin. Pulling the Run/SS below 0.8V puts the LTC3610 into a low quiescent current shut down state, whereas releasing the pin allows a 1.2 $\mu$ A current source to charge up the external soft-start capacitor. When



**Figure 6. Efficiency vs load current for the circuit of Figure 4**

the voltage on Run/SS reaches 1.5V, the LTC3610 begins operating with an initial clamp on  $I_{TH}$  of approximately 0.9V. This prevents current overshoot during start up. As the soft-start capacitor charges, the  $I_{TH}$  clamp increases, allowing normal operation at full load current. If the output voltage falls below 75% of the

regulated voltage, then a short-circuit fault is assumed. At this point, a 1.8 $\mu$ A current discharges capacitor  $C_{SS}$ . If the fault condition persists until Run/SS drops to 3.5V, the controller's overcurrent latch off turns off the MOSFETS until Run/SS is grounded and released. If latch off is not desired, a pull-up current source at Run/SS defeats this feature.

**Conclusion**

Few synchronous monolithic DC/DC converters are versatile enough to use in low power portable devices such as notebook and palmtop computers, as well as high power industrial distributed power systems. The LTC3610's broad input and output ranges, efficiency greater than 90% and high current capability make it a superior alternative to many solutions requiring separate power switches. **LT**

*LTC4067, continued from page 34*

OUT voltage rises above the BAT voltage, the charge cycle restarts where it left off.

At any time, the user may monitor both instantaneous charge current and instantaneous USB current by observing the PROG pin and CLPROG pin voltages respectively.

**Conclusion**

The LTC4067 satisfies the needs of voltage sensitive battery operated devices, replacing as many as three separate devices. With accuracy better than  $\pm 0.4\%$  on the battery float voltage, the LTC4067 is ideally suited for demanding high-precision applications. The LTC4067 offers both a power management

strategy that complies with USB port specifications as well as providing an advanced battery charger. The LTC4067 also offers overvoltage protection up to 13V, to protect itself as well as system devices in the event that an incorrect wall adapter is attached. **LT**

*LTC2355/56, continued from page 21*

power, and small package makes the LTC2356-14 ideal for high speed, portable applications including data acquisition, communications, and medical instrumentation.

The LTC2356-14 achieves 72.3dB SINAD and -82dB SFDR with a 1.4MHz input frequency. While measuring  $\pm 1.25$ V bipolar inputs differentially, the LTC2356-14's 80dB common mode rejection ratio allows users to eliminate ground loops and common mode noise. When the ADC is not converting, power dissipation can be reduced to 4mW in nap mode, with the internal 2.5V reference remaining active, and 13 $\mu$ W with all analog circuitry powered down in sleep mode.

For applications requiring a unipolar measurement, the LTC2355-14 measures 0V to 2.5V input signals, but is otherwise identical to the LTC2356-14. For lower resolution applications, the LTC2356-12 and LTC2355-12 are pin- and software-compatible 12-bit versions of the LTC2356-14 and LTC2355-14.

The LTC2355-14/LTC2356-14/LTC2355-12/LTC2356-12 ADCs are pin- and software-compatible with the LTC1403 2.8Msps ADC family, allowing users to easily upgrade their design for a 25% faster sample rate. Table 2 details these fast single-channel unipolar and bipolar ADCs.

**Summary**

With PCB real estate getting tighter and designers always searching for lower power ICs, fast data acquisition can be a challenge. Linear Technology's families of simultaneous sampling ADCs and fast single-channel ADCs make it possible to optimize solution size, power and cost. The pin- and software-compatible families of 6-channel, 2-channel and single-channel ADCs offer flexibility to upgrade from 12-bit resolution to 14-bit resolution. Whatever your motor control, power monitoring, or data acquisition system requires, Linear Technology has a fast SAR ADC to do the job. **LT**

# 0.25in<sup>2</sup> × 1.8mm Dual Output Converter for Li-Ion to 3.3V and 1.8V

by John Canfield

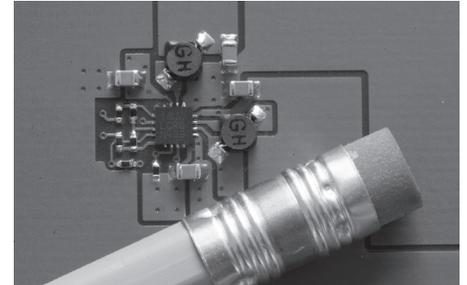
## Introduction

One quarter inch square. That is all the area needed for a complete Li-Ion to dual output, buck and buck-boost converter. Figure 1 shows a compact dual output converter made possible by the LTC3522—a complete, high efficiency, dual rail power supply solution in a 3mm × 3mm QFN. As shown, only a few external components are required, and they can all be low profile ( $\leq 1\text{mm}$ )—perfect for the demanding space requirements of even the most compact portable electronic devices.

The LTC3522 combines a monolithic buck-boost converter and synchronous buck converter in a single, low profile 0.75m × 3mm × 3mm 16-lead QFN. Soft-start and feedback loop compensation circuitry is included in the IC. An entire application circuit for a dual converter requires only the IC, inductors, bypass capacitors and feedback resistor dividers. Both converters maintain a low transient voltage deviation under full load step, even with small ceramic output capacitors. These features result in a simple application circuit as shown in Figure 2 and a total PCB area of less than 0.25 square inches as illustrated by Figure 1. The LTC3522 features a fixed internal switching frequency of 1.1MHz that allows for the use of low profile capacitors and inductors,

resulting in a total application height of only 1mm.

While requiring only a single inductor, the LTC3522 is capable of high efficiency fixed frequency operation with input voltages that are above, below, or equal to the output voltage. The buck-boost converter utilizes a proprietary switching algorithm to provide seamless transitions between buck and boost functional modes while simultaneously maximizing conversion efficiency. The buck-boost output



**Figure 1. Buck-boost and buck converter occupy less than 0.25in<sup>2</sup> of board space**

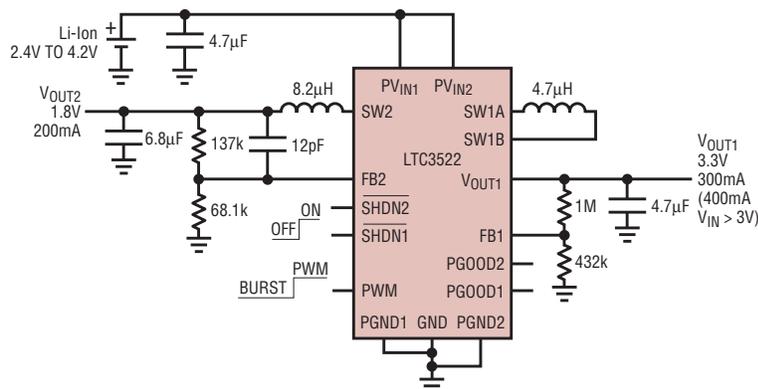
**The LTC3522 combines a monolithic buck-boost converter and synchronous buck converter in a single, low profile 0.75m × 3mm × 3mm 16-lead QFN.**

**Circuitry for soft-start and feedback loop compensation is integrated into the IC. An entire application circuit for a dual converter requires only the LTC3522 and a minimal number of external components.**

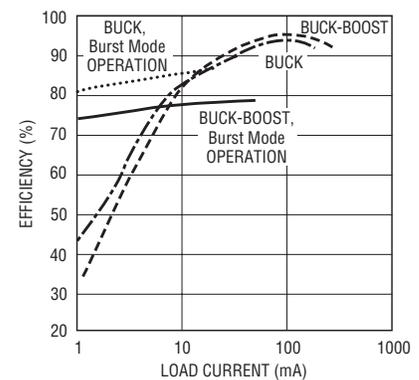
voltage can be set as low as 2.2V or as high as 5.25V. With a 3.3V output, the buck-boost converter is able to supply a 300mA load current over the full 2.4V to 5.5V input voltage range. When powered by a standard Li-Ion battery with a minimum voltage of 3V, a 400mA load can be supported.

The LTC3522 buck converter features internally compensated current mode control that ensures a rapid transient response over a wide range of output capacitor values. The buck converter can supply a load current of up to 200mA over the entire input voltage range and its output voltage can be set as low as 0.6V. The buck converter transitions smoothly to 100% duty cycle operation to extend battery life in low dropout operation.

Despite its tiny size, the LTC3522 boasts an efficiency of up to 95% for

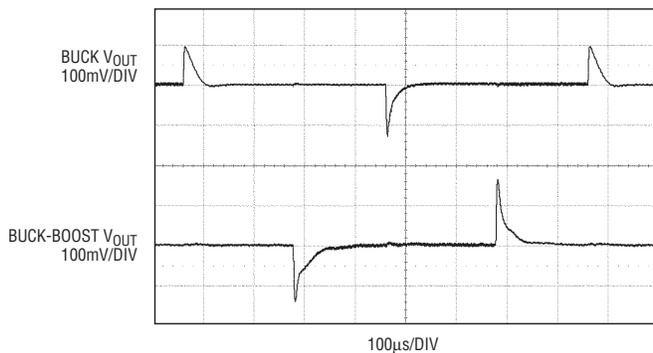


**Figure 2. Li-Ion to 3.3V at 300mA and 1.8V at 200mA**



BUCK-BOOST L = COILCRAFT MSS6132 – 4.7µH  
BUCK L = COILCRAFT MSS6132 – 8.2µH

**Figure 3. Efficiency vs load current**



**Figure 4. Alternating load step responses**

each converter and incorporates a variety of useful features. Both converters include an internal, closed-loop soft start to ensure a reliable output voltage rise time, independent of loading and output capacitor value. In addition, each converter includes its own open-drain power-good indicator, which allows for undervoltage fault detection and sequenced start-up. Each converter can be independently enabled. With both converters disabled, the total supply current is reduced to under 1µA.

**Efficiency**

Figure 3 shows the efficiency of each converter for the circuit of Figure 2. The buck-boost converter reaches a peak efficiency of 95%, while the buck converter peaks at 94%. In PWM mode, both converters are greater than 90% efficient at all load currents above 30mA.

Pin selectable Burst Mode® operation improves efficiency at light load currents. In Burst Mode, the total qui-

escent current is reduced to only 25µA with both converters enabled. In noise sensitive applications, both converters can be forced into low noise, fixed frequency PWM operation by connecting the PWM pin to V<sub>IN</sub>. Alternatively, the PWM pin can be driven dynamically in the application to provide low noise performance during critical phases of operation.

**Supply Sequencing**

Many dual supply applications require that the supply rails power up in a particular order. A common example is a microprocessor in which the core supply voltage must be up and in regulation before the peripheral supply powering the output pin drivers is enabled. This ensures that the core logic is functioning before the outputs become active, thereby preventing erratic output fluctuations during power-up.

The LTC3522 has an independent power-good output for each converter. This allows the two output voltages to

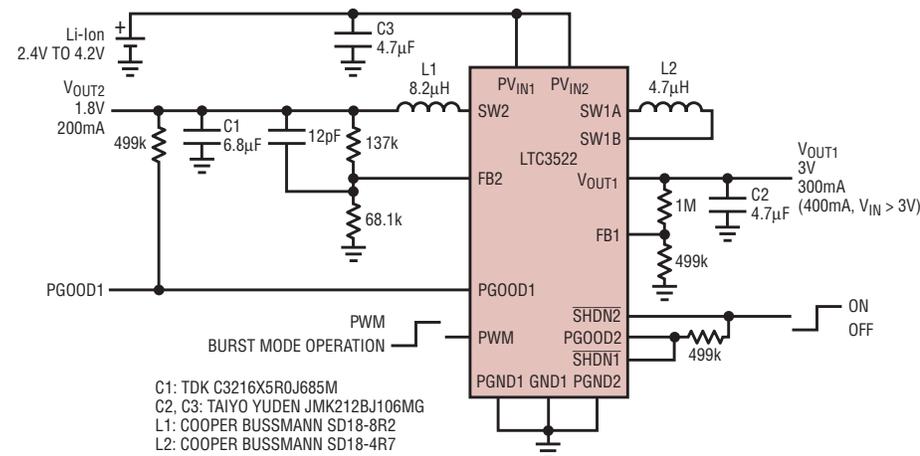
be sequenced in either order without requiring any additional external components. Figure 5 shows a sequenced LTC3522 application circuit that waits for the 1.8V buck output rail to reach regulation before enabling the buck-boost converter to power the 3.0V output rail. This is accomplished by simply connecting the SHDN1 pin to the buck power-good output, PGOOD2. With the external enable signal held low, both converters are disabled. When the external enable is brought high, the buck converter is immediately enabled. The buck-boost converter remains disabled until PGOOD2 goes high, indicating that the buck converter has reached regulation.

**Inter-Channel Performance**

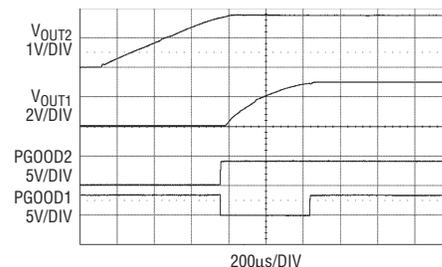
While in PWM mode, both converters operate synchronously from a common 1.1Mhz oscillator. This minimizes the interaction between the two converters so that load steps on the output of one converter have little impact on the opposite output. For example, Figure 4 shows both output voltages as a 20mA to 200mA load step is applied to the buck channel and a 0mA to 300mA load step is applied to the buck-boost channel. In this case, even with small 4.7µF output capacitors on each converter, the interaction between channels is minimal.

**Conclusion**

The LTC3522 provides a complete, sequenced dual rail power supply solution in a compact footprint. Its high efficiency and exceptional performance make the LTC3522 well suited for even the most demanding portable applications. 



**Figure 5. Sequenced power-up application**



**Figure 6. Sequenced power-up waveforms**

# Sub- $\mu\text{A}$ RMS Current Measurement for Quartz Crystals

by Jim Williams

Quartz crystal RMS operating current is critical to long-term stability, temperature coefficient and reliability. Accurate determination of RMS crystal current, especially in micropower types, is complicated by the necessity to minimize introduced parasitics, particularly capacitance, which corrupt crystal operation.

Figure 1's high gain, low noise amplifier combines with a commercially available closed core current

probe to permit the measurement. An RMS-to-DC converter supplies the RMS value. The quartz crystal test circuit shown in dashed lines exemplifies a typical measurement situation. The Tektronix CT-1 current probe monitors crystal current while introducing minimal parasitic loading. The probe's  $50\Omega$  terminated output is fed to A1. A1 and A2 take a closed loop gain of 1120; excess gain over a nominal gain of 1000 corrects for the

CT-1's 12% low frequency gain error at 32.768kHz.<sup>1</sup> A3 and A4 contribute a gain of 200, resulting in total amplifier gain of 224,000. This figure results in a  $1\text{V}/\mu\text{A}$  scale factor at A4 referred to the gain corrected CT-1's output. A4's LTC1563-2 bandpass filtered output feeds an LTC1968-based RMS-to-DC converter (A5), which provides the circuit's output. The signal processing path constitutes an extremely narrow band amplifier tuned to the crystal's

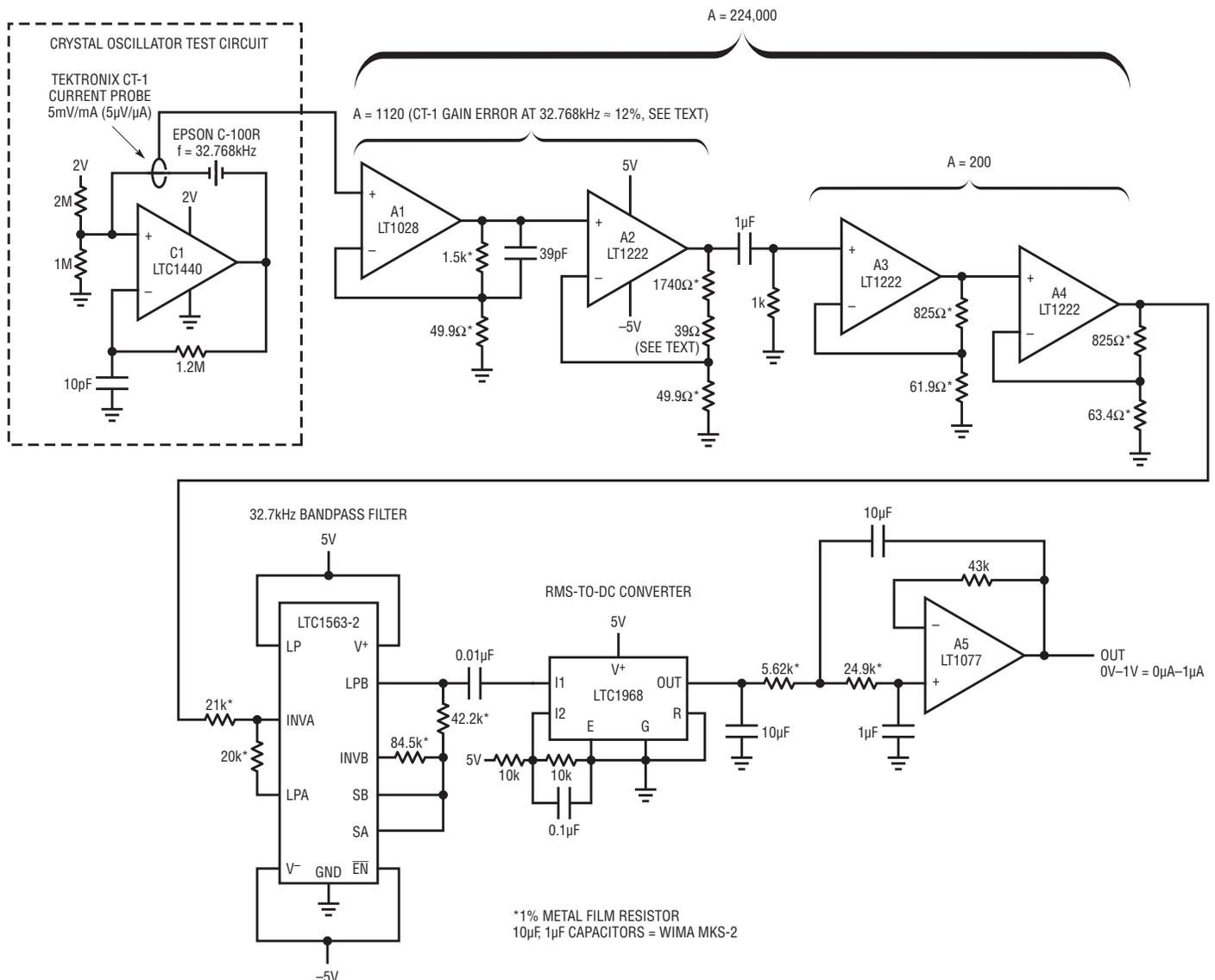
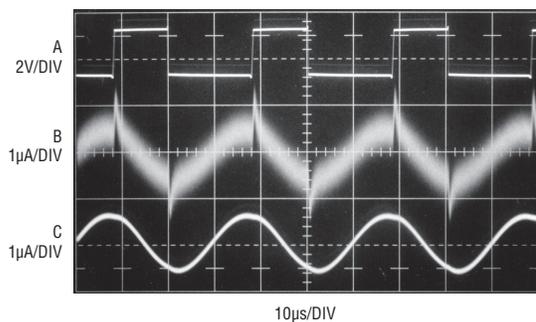


Figure 1. Op amps A1-A4 furnish gain of > 200,000, permitting sub- $\mu\text{A}$  crystal current measurement. The LTC1563-2 bandpass filter smooths residual noise while providing unity gain at 32.768kHz. The LTC1968 RMS-to-DC converter supplies RMS calibrated output.



**Figure 2. The 32.768kHz output of the crystal oscillator (Trace A) and crystal current monitored at A4 output (Trace B) and the RMS-to-DC converter input (Trace C). Peaks in Trace B's unfiltered waveform derive from inherent and parasitic paths shunting the crystal.**

frequency. Figure 2 shows typical circuit waveforms. Crystal drive, taken at CI's output (trace A), causes a 530nA RMS crystal current, which is represented at A4's output (Trace B) and the RMS-to-DC converter input (Trace C). Peaking visible in Trace B's unfiltered

presentation derive from inherent and parasitic paths shunting crystal.

Typical circuit accuracy is 5%. Uncertainty terms include the transformer's tolerances, its approximately 1.5pF loading and resistor/RMS-to-DC converter error. Calibrating the

circuit reduces error to less than 1%. Calibration involves driving the transformer with 1µA at 32.7kHz. This is facilitated by biasing a 100k, 0.1% resistor with an oscillator set at 0.1V output. The output voltage should be verified with an RMS voltmeter having appropriate accuracy. Figure 1 is calibrated by padding A2's gain with a small resistive correction, typically 39Ω. **LT**

**Notes**

1 The validity of this gain error correction at one sinusoidal frequency—32.768kHz—was investigated with a 7-sample group of Tektronix CT-1s. Device outputs were collectively within 0.5% of 12% down for a 1.00µA, 32.768kHz sinusoidal input current. Although this tends to support the measurement scheme, it is worth noting that these results are as measured. Tektronix does not guarantee performance below the specified -3dB, 25kHz low frequency roll-off.

# New Device Cameos

## High Voltage Dual Input Li-Ion Battery Charger

The LTC4075HVX is a standalone linear charger that is capable of charging a single-cell Li-Ion/Polymer battery from both wall adapter and USB inputs. The charger can detect power at the inputs and automatically select the appropriate power source for charging.

No external sense resistor or blocking diode is required for charging due to the internal MOSFET architecture. The LTC4075HVX features a maximum 22V rating for both wall adapter and USB inputs although charging stops if the selected power source exceeds the overvoltage limit (typical 6V). Internal thermal feedback regulates the battery charge current to maintain a constant die temperature during high power operation or high ambient temperature conditions. The float voltage is fixed at 4.2V and the charge current is programmed with an external resistor. The LTC4075HVX terminates the charge cycle when the charge current drops below the programmed termination threshold after the final float voltage is reached.

Other features include automatic recharge, undervoltage lockout,

charge status outputs, and "power present" status outputs to indicate the presence of wall adapter or USB power. No trickle charge allows full current from the charger when a load is connected directly to the battery.

## Small 1.8A Step-Down Regulator Switches at 4MHz for Space-Sensitive Applications

The LTC3568 is a 10-lead DFN, synchronous, step-down, current mode, DC/DC converter, intended for medium power applications. It operates within a 2.5V to 5.5V input voltage range and switches at up to 4MHz, making it possible to use tiny capacitors and inductors that are under 1mm in height. The output of the LTC3568 is adjustable from 0.8V to 5V, and its 0.11Ω switches allows up to 1.8A of output current at high efficiency. By using the LTC3568 in a small 3mm x 3mm, 10-lead DFN package, a complete DC/DC converter can consume less than 0.3 square inches of board real estate.

Efficiency is extremely important in battery-powered applications, and the LTC3568 keeps efficiency high with an automatic, power saving Burst Mode

operation, which reduces gate charge losses at low load currents. With no load, the part only draws 60µA, and in shutdown, the device draws less than 1µA, making it ideal for low current applications.

The LTC3568 uses a current-mode, constant frequency architecture that benefits noise sensitive applications. Burst Mode operation is an efficient solution for low current applications, but sometimes noise suppression is a priority. To reduce noise problems, a pulse-skipping mode and a forced continuous mode are available, which decreases the ripple noise at low currents. Although not as efficient as Burst Mode operation at low currents, pulse-skipping mode and forced continuous mode still provide high efficiency for moderate loads. In dropout, the internal P-channel MOSFET switch is turned on continuously, thereby maximizing the usable battery life.

A Power Good output is available for power supply monitoring or for Power On Reset use. Internal overvoltage and undervoltage comparators pull the open-drain PGOOD output low if the output voltages are not within about ±7.5%.

The LTC3568's small size, high efficiency, low component count and flexibility make it an ideal DC/DC converter for portable devices. **LT**

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