

IN THIS ISSUE

our new look 2

dual output step-down regulator with DCR sensing in a 5mm x 5mm QFN 9

accurate battery gas gauges with I<sup>2</sup>C interface 12

dual buck regulator operates outside of AM radio band 20

eight 16-bit V<sub>OUT</sub> DACs in a 4mm x 5mm QFN 24

dual-phase converter for 1.2V at 50A with DCR sensing 28

## Energy Harvester Produces Power from Local Environment, Eliminating Batteries in Wireless Sensors

Michael Whitaker

Advances in low power technology are making it easier to create wireless sensor networks in a wide range of applications, from remote sensing to HVAC monitoring, asset tracking and industrial automation. The problem is that even wireless sensors require batteries that must be regularly replaced—a costly and cumbersome maintenance project. A better wireless power solution would be to harvest ambient mechanical, thermal or electromagnetic energy from the sensor’s local environment.

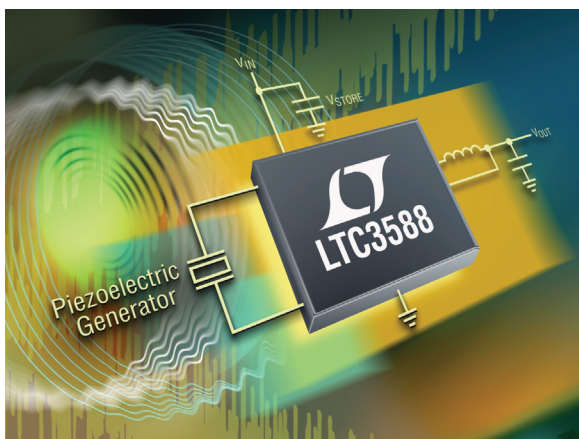
Typically, harvestable ambient power is on the order of tens of microwatts, so energy harvesting requires careful power management in order to successfully capture microwatts of ambient power and store it in a useable energy reservoir. One common form of ambient energy is mechanical

vibration energy, which can be caused by motors running in a factory, airflow across a fan blade or even by a moving vehicle. A piezoelectric transducer can be used to convert these forms of vibration energy into electrical energy, which in turn can be used to power circuitry.

To manage the energy harvesting and the energy release to the system, the LTC<sup>®</sup>3588-1 piezoelectric energy harvesting power supply (Figure 1) integrates a low loss internal bridge rectifier with a synchronous step-down DC/DC converter. It uses an efficient energy harvesting algorithm to collect and store energy from high impedance piezoelectric elements, which can have short-circuit currents on the order of tens of microamps.

Energy harvesting systems must often support peak load currents that are much higher than a piezoelectric element can produce, so the LTC3588-1 accumulates energy that can be released to the load in short power bursts. Of course, for continuous operation these power

*(continued on page 4)*



Piezoelectric energy harvesting power supply

# In this issue...

## COVER ARTICLE

Energy Harvester Produces Power from Local Environment, Eliminating Batteries in Wireless Sensors

**Michael Whitaker**

1

## DESIGN FEATURES

Dual Output Step-Down Regulator Features Pin Selectable Outputs, DCR Sensing, Reverse Current Protection and a 5mm × 5mm QFN

**Stephanie Dai**

9

Tiny, Accurate Battery Gas Gauges with Easy-to-Use I<sup>2</sup>C Interface and Optional Integrated Precision Sense Resistors

**Christoph Schwoerer, Axel Klein and Bernhard Engl**

12

140W Monolithic Switching Regulator Simplifies Constant-Current/Constant-Voltage Regulation

**Eric Young**

16

2MHz Dual Buck Regulator Operates Outside of AM Radio Band When Delivering 3.3V and 1.8V from 16V Input

**Pit-Leong Wong**

20

Eight 16-Bit, Low INL, V<sub>OUT</sub> DACs in a 4mm × 5mm QFN Package: Unparalleled Density and Flexibility

**Leo Chen**

24

## DESIGN IDEAS

6mm × 6mm DC/DC Controller for High Current DCR Sensing Applications

**Eric Gu, Theo Phillips, Mike Shriver and Kerry Holliday**

28

Maximize Cycle Life of Rechargeable Battery Packs with Multicell Monitor IC

**Jon Munson**

30

Dual 500mA  $\mu$ Power LDO Features Independent 1.8V–20V Inputs and Easy Sequencing in a 4mm × 3mm DFN

**Molly Zhu**

33

product briefs

34

back page circuits

36

# Design Innovation: Our New Look

**Bob Dobkin**, Co-founder, Vice President, Engineering & CTO

Design innovation. That's what we're about—in our products and here in the newly updated *Linear Technology* magazine. After nearly two decades in a two-color format, we have updated its design while maintaining the deep technical focus you've come to expect.

To complement the technical innovation that defines Linear's products, we have added color and features to make this publication more readable, useful and inviting. It's our goal to continue to provide you with an informative publication, worth keeping.

The new design is optimized for delivery both electronically and in print for ease of download or printing on a laser printer. The addition of color makes for more compelling reading and better understanding of the technical material.

Over the years, we've referred to this publication as "LT magazine," so the new name is fitting. Since all the material in the publication is new circuitry, we have added a new subtitle, *Journal of Analog Innovation*, to emphasize the technical sophistication.

As before, *LT* carries in-depth features and design ideas, plus a new section, "highlights from circuits.linear.com" on the back page. What hasn't changed is what we're about. After more than 28 years delivering innovative high performance analog solutions, we're still at it—focused on solving the hard-to-do analog problems. We're confident that the designs discussed in *LT* will give your end-products a performance edge.

*LT* is your publication and we welcome your comments, ideas and suggestions—both for the products you need and the ways you'd like to receive information. We hope you like our latest design innovation. ■



# Linear in the News

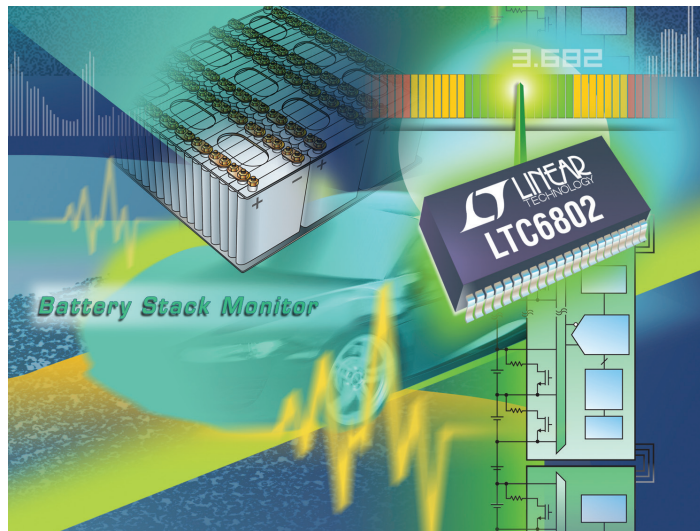
## μMODULE SEMINARS IN EUROPE

Designers today are challenged with the increased complexity of power design, a growing number of system voltage rails and with designing power management solutions to drive FPGAs and DSPs. Linear's μModule® DC/DC regulators provide a complete circuit in a tiny package, simplifying system power design, saving valuable board space, increasing efficiency, and reducing development time and risk.

To ease the design challenge, Linear Technology and its partners are offering a series of free, half-day seminars across Europe on the use of its high performance DC/DC μModule regulators. The seminars, which include lunch, give an overview of high end power needs for complex systems, discuss the power μModule regulator concept, and include a design lab with demonstrations of tools and demo boards. The seminars are held in March, April and May at various locations in the UK, Ireland, Sweden, Denmark, Italy, France, Germany, Austria, Switzerland, Belgium and the Netherlands. For complete information, visit [www.linear.com/designtools/EasyAnalogSeminars.html](http://www.linear.com/designtools/EasyAnalogSeminars.html).

## PARTICIPATION AT IIC-CHINA

Linear had a booth at the IIC-china exhibition in Shenzhen on March 4–5 and in Chengdu on March 11–12. As the China electronics market continues to grow in scale and sophistication, Linear is well positioned to grow in that market. Linear's product emphasis on such markets as industrial, communications and automotive fits well with the China market, which is seeing growth in all these segments.



## ANALOG PRODUCT OF THE YEAR

The LTC6802 is a highly integrated multicell battery monitoring IC capable of precisely measuring the voltages of up to 12 series-connected lithium-ion battery cells. With a maximum measurement error of less than 0.25%, the LTC6802 enables battery cells to operate over their full charge and discharge limits, maximizing lifetime and useful battery capacity.

The industrial market demands products with high precision, quality and reliability—areas in which Linear Technology excels. The automotive market is being fueled by the push to develop high efficiency hybrid and electric vehicles. In addition, the overall electronic content in vehicles is increasing rapidly, with analysts estimating that electronic content in cars will reach 15% of a new vehicle's cost by 2012. There is an explosion underway in the need for communications infrastructure equipment to keep up with the demand from the growing use of smart phones and other broadband wireless devices.

At IIC-china, Linear showcased power μModule DC/DC regulators, battery stack monitors for hybrid and electric vehicles, energy harvesting products that capture ambient energy to power sensors wirelessly, isolated μModule transceivers + power, communications μModule

products, RF products for communications infrastructure, digital power management, LED drivers and power management ICs.

## ANALOG PRODUCT OF THE YEAR

At *Electronics Weekly's* annual Elektra Awards ceremony, held in London in December, Linear Technology's LTC6802 Battery Stack Monitor for Hybrid/Electric Vehicles was named Semiconductor Product of the Year—Analogue. The product was selected based on its performance, design flexibility and suitability for the application.

The LTC6802 is a highly integrated multicell battery monitoring IC capable of precisely measuring the voltages of up to 12 series-connected lithium-ion battery cells. Applications for the LTC6802 include electric and hybrid electric vehicles, scooters, motorcycles, golf carts, medical equipment and uninterruptible power supply systems. ■

The LTC3588-1 interfaces with the piezo through its internal low loss bridge rectifier accessible via the PZ1 and PZ2 pins. The rectified output is stored on the  $V_{IN}$  capacitor. At typical  $10\mu\text{A}$  piezoelectric currents, the voltage drop associated with the bridge rectifier is on the order of  $400\text{mV}$ .

(continued from page 1)

bursts must occur at a low duty cycle, such that the total output energy during the burst does not exceed the average source power integrated over an energy accumulation cycle. A sensor system that makes a measurement at regular intervals, transmits data and powers down in between is a prime candidate for an energy harvesting solution.

### KEY TO HARVESTING IS LOW QUIESCENT CURRENT

The energy harvesting process relies on a low quiescent current energy accumulation phase. The LTC3588-1 enables this through an undervoltage lockout (UVLO) mode with a wide hysteresis window that draws less than a microamp of quiescent current. The UVLO mode allows charge to build up on an input capacitor until an internal buck converter can efficiently transfer a portion of the stored charge to the output.

Figure 2 shows a profile of the quiescent current in UVLO, which is monotonic with  $V_{IN}$  so that a current source as low as  $700\text{nA}$  could charge the input capacitor

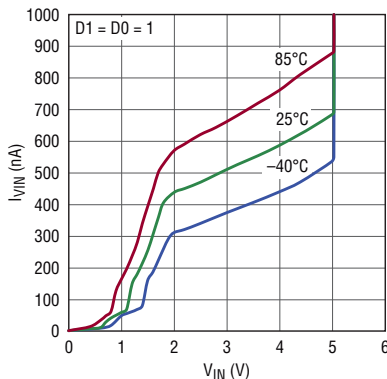
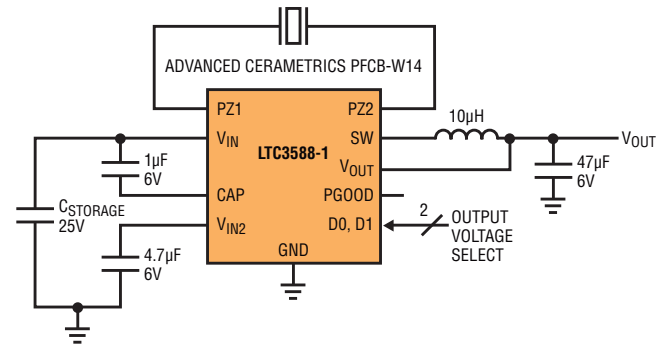


Figure 2.  $I_{VIN}$  in UVLO vs  $V_{IN}$

Figure 1. Piezoelectric energy harvesting power supply



to the UVLO rising threshold and result in a regulated output. Once in regulation, the LTC3588-1 enters a sleep state in which both input and output quiescent currents are minimal. For instance, at  $V_{IN} = 4.5\text{V}$ , with the output in regulation, the quiescent current is only  $950\text{nA}$ . The buck converter then turns on and off as needed to maintain regulation. Low quiescent current in both the sleep and UVLO modes allows as much energy to be accumulated in the input reservoir capacitor as possible, even if the source current available is very low.

When  $v_{IN}$  reaches the UVLO rising threshold, the high efficiency integrated synchronous buck converter turns on and begins to transfer energy from the input capacitor to the output capacitor. The buck regulator uses a hysteretic voltage algorithm to control the output via internal feedback from the  $V_{OUT}$  sense pin. It charges the output capacitor through an inductor to a value slightly higher than the regulation point by ramping the inductor current up to  $250\text{mA}$  through an internal PMOS switch and then ramping it down to zero current through an internal NMOS switch. This efficiently delivers energy to the output capacitor.

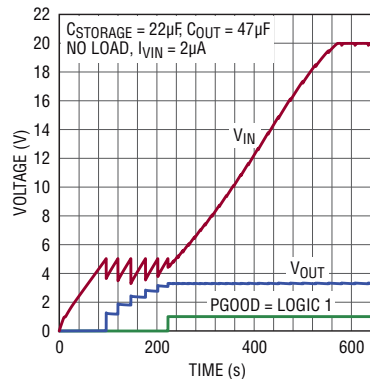


Figure 3. A 3.3V regulator start-up profile

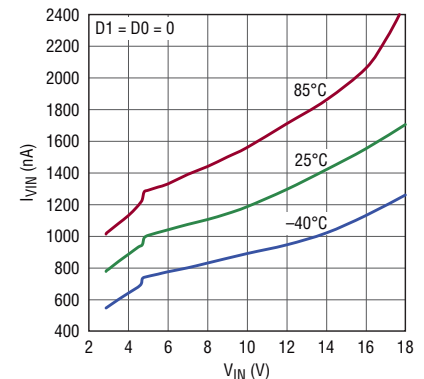
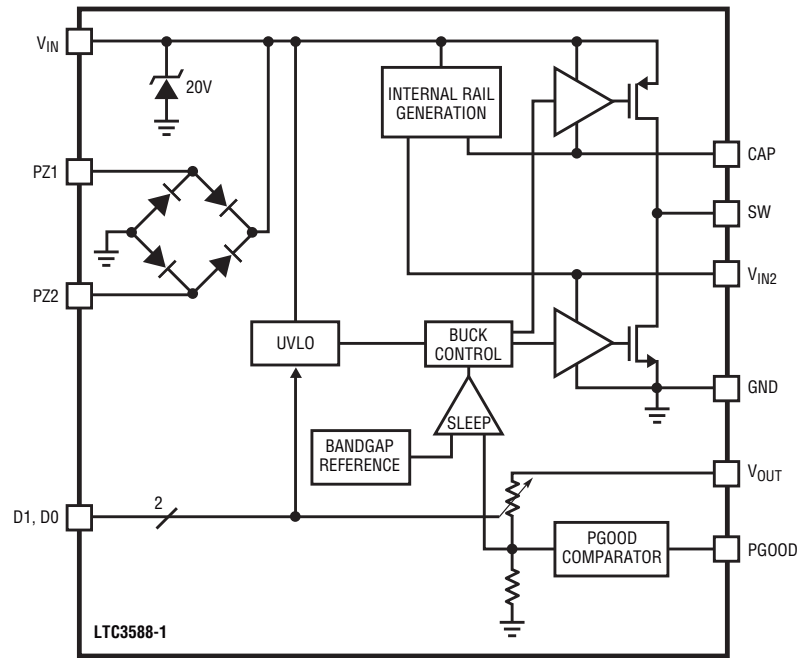


Figure 4.  $I_{VIN}$  in sleep vs  $V_{IN}$

Figure 8. Block diagram of the LTC3588-1



If the input voltage falls below the UVLO falling threshold before the output voltage reaches regulation, the buck converter shuts off and is not turned on again until the input voltage rises above the UVLO rising threshold. During this time the leakage on the V<sub>OUT</sub> sense pin is no greater than 90nA and the output voltage remains near the level it had reached when the buck was switching. Figure 3 shows a typical start-up waveform of the LTC3588-1 charged by a 2μA current source.

When the synchronous buck brings the output voltage into regulation the converter enters a low quiescent current sleep state that monitors the output voltage with a sleep comparator. During this operating mode, load current is provided by the buck output capacitor. When the output voltage falls below the regulation point the buck regulator wakes up and the cycle repeats. This hysteretic method of providing a regulated output minimizes losses associated with FET switching and makes it possible to efficiently regulate at very light loads.

The buck delivers up to 100mA of average load current when it is switching. Four output voltages, 1.8V, 2.5V, 3.3V and 3.6V, are pin selectable and accommodate powering of microprocessors, sensors and wireless transmitters. Figure 4 shows the extremely low quiescent current while in regulation and in sleep, which allows for efficient operation at light loads. Although the quiescent current of the buck regulator while switching is much greater than the sleep quiescent current, it is still a small percentage of the load current, which results in high efficiency over a wide range of load conditions (Figure 5).

The buck operates only when sufficient energy has been accumulated in the input capacitor, and it transfers energy to the output in short bursts, much shorter than the time it takes to accumulate energy. When the buck operating quiescent current is averaged over an entire accumulation/burst period, the average quiescent current is very low, easily accommodating sources that harvest small amounts of ambient energy. The extremely low quiescent current in regulation also allows the LTC3588-1 to achieve high efficiency at loads under 100μA as shown in Figure 5.

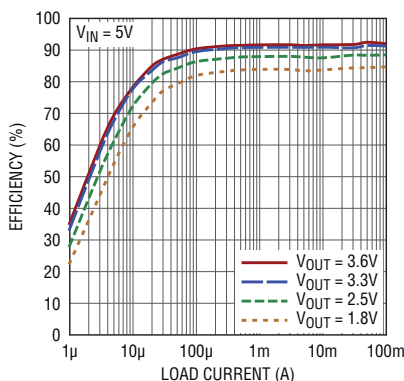


Figure 5. Efficiency vs I<sub>LOAD</sub>

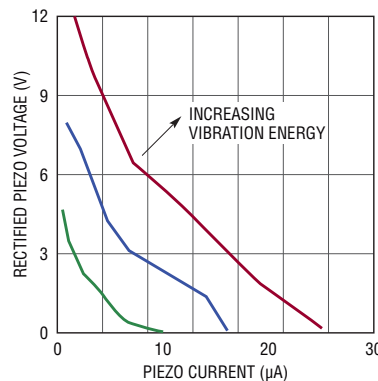


Figure 6. Typical piezoelectric load lines for Piezo Systems T220-A4-503X

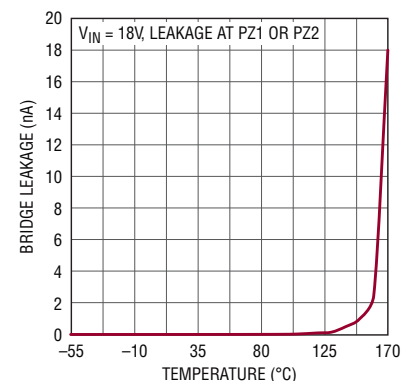
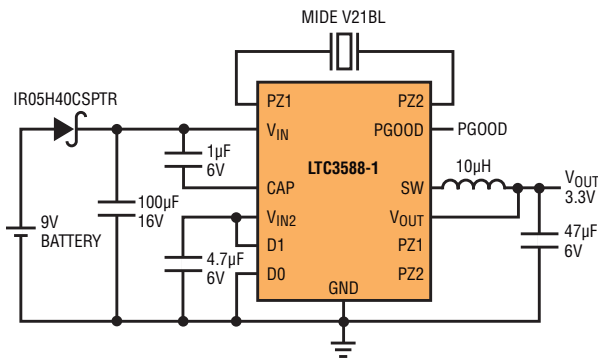


Figure 7. The internal bridge rectifier outperforms discrete solutions

Though an energy harvesting system can eliminate the need for batteries, it can also supplement a battery solution.

**Figure 9. Piezo energy harvester with battery backup**



### REAPING VIBRATION ENERGY

Piezoelectric elements convert mechanical energy, typically vibration energy, into electrical energy. Piezoelectric elements can be made out of PZT (lead zirconate titanate) ceramics, PVDF (polyvinylidene fluoride) or other composites. Ceramic piezoelectric elements exhibit a piezoelectric effect when the crystal structure of the ceramic is compressed and internal dipole movement produces a voltage. Polymer elements comprised of long-chain molecules produce a voltage when flexed as molecules repel each other. Ceramics are often used under direct pressure while a polymer can be flexed more readily.

A wide range of piezoelectric elements are available and produce a variety of open circuit voltages and short-circuit currents. The open circuit voltage and short-circuit current form a “load line” for the piezoelectric element that increases with available vibration energy as shown in Figure 6. The LTC3588-1 can handle up to 20V at its input, at which point a protective shunt safeguards against an overvoltage condition on  $V_{IN}$ . If ample ambient vibration causes a piezoelectric element to produce

more energy than the LTC3588-1 needs, the shunt consumes the excess power, effectively clamping the piezo on its load line.

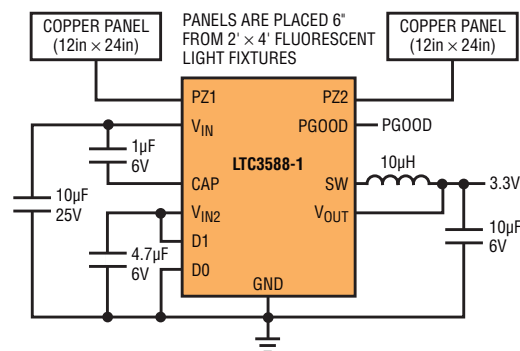
The LTC3588-1 interfaces with the piezo through its internal low loss bridge rectifier accessible via the PZ1 and PZ2 pins. The rectified output is stored on the  $V_{IN}$  capacitor. At typical 10µA piezoelectric currents, the voltage drop associated with the bridge rectifier is on the order of 400mV. The bridge rectifier also suits a variety of other input sources by featuring less than 1nA of reverse leakage at 125°C (Figure 7), a bandwidth greater than 1MHz and ability to carry 50mA.

Ambient vibrations can be characterized in order to select a piezo with optimal characteristics. The frequency and force of the vibration as well as the desired interval between use of the LTC3588-1’s output capacitor reservoir and the amount of energy required at each burst can help to determine the best piezoelectric element. In this way, a system can be designed so that it performs its task as often as the amount of available energy allows. In some cases, optimization of the piezoelectric element may not be necessary as just the capability to harvest any amount of energy may be attractive.

### OPTIONS FOR ENERGY STORAGE

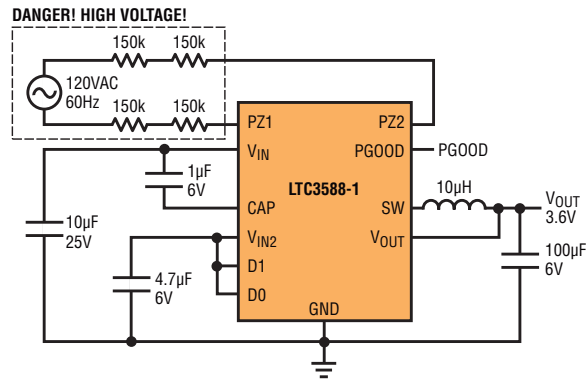
Harvested energy can be stored on the input capacitor or the output capacitor. The wide input range takes advantage of the fact that energy storage on a capacitor is proportional to the square of the capacitor voltage. After the output voltage is brought into regulation any excess energy is stored on the input capacitor and its voltage increases. When a load exists at the output, the buck can efficiently transfer energy stored at a high voltage to the regulated output. While

**Figure 10. Electric field energy harvester**



The LTC3588-1 can harvest other sources of energy besides the ambient vibration energy available from a piezoelectric element. The integrated bridge rectifier allows many other AC sources to power the LTC3588-1.

Figure 11. AC line powered 3.6V buck regulator



**DANGEROUS AND LETHAL POTENTIALS ARE PRESENT IN OFFLINE CIRCUITS!**

Before proceeding any further, the reader is warned that caution must be used in the construction, testing and use of offline circuits. Extreme caution must be used in working with and making connections to these circuits.

**REPEAT:** Offline circuits contain dangerous, AC line-connected high voltage potentials. **Use caution.** All testing performed on an offline circuit must be done with an isolation transformer connected between the offline circuit's input and the AC line. Users and constructors of offline circuits must observe this precaution when connecting test equipment to the circuit to avoid electric shock.

**REPEAT:** An isolation transformer must be connected between the circuit input and the AC line if any test equipment is to be connected.

energy storage at the input utilizes the high voltage at the input, the load current is limited to the 100mA the buck converter can supply. If larger transient loads need to be serviced, the output capacitor can be sized to support a larger current for the duration of the transient.

A PGOOD output exists that can help with power management. PGOOD transitions high (referred to  $V_{OUT}$ ) the first time the output reaches regulation and stays high until the output falls to 92% of the regulation point. PGOOD can be used to trigger a system load. For example, a current burst could begin when PGOOD goes high and would continuously deplete the

output capacitor until PGOOD went low. In some cases, using every last joule is important and the PGOOD pin will remain high if the output is still within 92% of the regulation point, even if the input falls below the lower UVLO threshold (as might happen if vibrations cease).

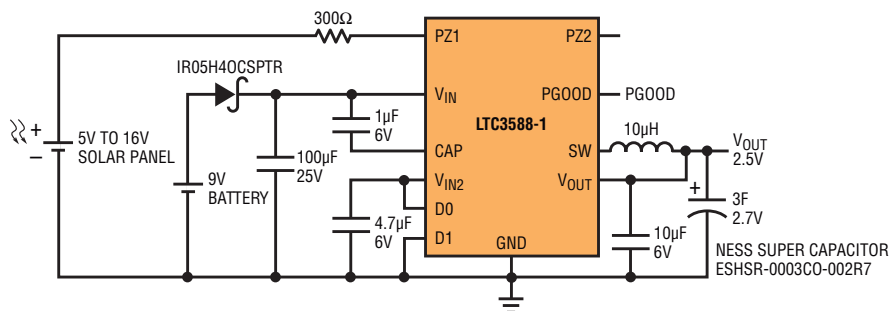
**THE LTC3588-1 EXTENDS BATTERY LIFE**

Though an energy harvesting system can eliminate the need for batteries, it can also supplement a battery solution. The system can be configured such that when ambient energy is available, the battery is unloaded, but when the ambient source disappears, the battery engages and serves as the backup power supply. This approach

not only improves reliability, but it can also lead to a more responsive system. For example, an energy harvesting sensor node placed on a mobile asset, such as a tractor trailer, may gather energy when the trailer is on the road. When the truck is parked and there is no vibration, a battery backup still allows polling of the asset.

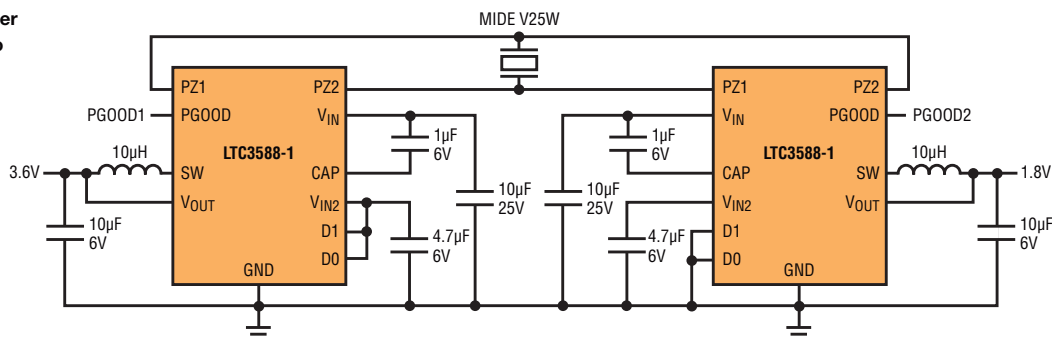
The battery backup circuit in Figure 9 shows a 9v battery with a series blocking diode connected to  $V_{IN}$ . The piezo charges  $V_{IN}$  through the internal bridge rectifier and the blocking diode prevents reverse current from flowing into the battery. A 9v battery is shown, but any stack of batteries of a given chemistry can be used as long as the battery stack voltage does

Figure 12. Solar panel powering the LTC3588-1



Not limited to AC sources, DC sources such as solar panels and thermoelectric couplers can be used to power the LTC3588-1.

Figure 13. Dual rail power supply with single piezo



not exceed 18V, the maximum voltage that can be applied to  $V_{IN}$  by an external low impedance source. When designing a battery backup system, the piezoelectric transducer and battery should be chosen such that the peak piezo voltage exceeds the battery voltage. This allows the piezo to “take over” and power the LTC3588-1.

### A WEALTH OF ALTERNATIVE ENERGY SOLUTIONS

The LTC3588-1 can harvest other sources of energy besides the ambient vibration energy available from a piezoelectric element. The integrated bridge rectifier allows many other AC sources to power the LTC3588-1. For example, the fluorescent light energy harvester shown in Figure 10 capacitively harvests the alternating electric field radiated by an AC powered fluorescent light tube. Copper panels can be placed above the light tube on the light fixture to harness the energy from the electric field produced by the light tube and feed that energy to the LTC3588-1 and the integrated bridge rectifier. Such a harvester can be used throughout buildings to power HVAC sensor nodes.

Another useful application of the LTC3588-1 involves powering the IC from the AC line voltage with current limiting resistors as shown in Figure 11. This offers a low cost, transformer-free solution for simple plug-in applications. Appropriate UL guidelines should be followed when designing circuits connecting directly to the line voltage.

Not limited to AC sources, DC sources such as solar panels and thermoelectric couplers can be used to power the LTC3588-1 as shown in Figure 12. Such sources can connect to one of the PZ1/PZ2 inputs to utilize the reverse current protection that the bridge would provide. They can also be diode-ored together to the  $V_{IN}$  pin with external diodes. This facilitates the use of multiple solar panels aimed in different directions to catch the sun at different times during the day.

### MULTIPLE OUTPUT RAILS SHARE A SINGLE PIEZO SOURCE

Many systems require multiple rails to power different components. A microprocessor may use 1.8V but a wireless transmitter may need 3.6V. Two LTC3588-1 devices can be connected to

one piezoelectric element and simultaneously provide power to each output as shown in Figure 13. This setup features automatic supply sequencing as the LTC3588-1 with the lower voltage output (i.e., lower  $UVLO$  rising threshold) comes up first. As the piezo provides input power both  $V_{IN}$  rails initially come up together, but when one output starts drawing power, only its corresponding  $V_{IN}$  falls as the bridges of each LTC3588-1 provide isolation. Input piezo energy is then directed to this lower voltage capacitor until both  $V_{IN}$  rails are again equal. This configuration is expandable to multiple LTC3588 devices powered by a single piezo as long as the piezo can support the sum total of the quiescent currents from each LTC3588-1.

### CONCLUSION

The LTC3588-1 provides a unique power solution for emerging wireless sensor technologies. With extremely low quiescent current and an efficient energy harvesting solution it makes distributed sensor networks easier to deploy. Sensors can now be used in remote locations without worrying about battery life. ■



# Dual Output Step-Down Regulator Features Pin Selectable Outputs, DCR Sensing, Reverse Current Protection and a 5mm × 5mm QFN

Stephanie Dai

The LTC3865 is a high performance step-down controller with two constant frequency, current mode, synchronous buck controllers and on-chip drivers. It offers high output current capability over a wide input range. An important feature offered by the LTC3865 is its highly accurate programmable output voltage. Internal precision feedback resistors make it possible to select from nine different output voltages via two VID pins. The internal resistors reduce the number of external components and assure 1% accuracy for low voltage rails.

The LTC3865 is suitable for applications with input voltages up to 38V and output voltages up to 5V. It can be synchronized to a frequency of up to 750kHz and comes in a compact 5mm × 5mm QFN package. The part is also capable of inductor DCR sensing, allowing for increased efficiencies at higher load currents. These features are ideal for wide input voltage range, high current applications where design solution footprint size is restricted.

## PIN SELECTABLE OUTPUTS

The LTC3865 features pin programmable output voltages. Tying each channel's two VID pins to INTV<sub>CC</sub>, GND or leaving

them floating can result in nine different output voltages from 0.6V to 5V (see Table 1). Pin programming eliminates at least four external feedback resistors, making the overall design solution space conservative and cost effective. If an application requires an output voltage not supported by pin programming, one still has the option to use external resistors to set the output voltage. Since the LTC3865 integrates precision feedback resistors, it can achieve 1% output accuracy for outputs from 0.6V to 1.8V and 1.5% percent output accuracy for 2.5V to 5V, with this accuracy maintained over the temperature range of -40°C to 85°C.

## R<sub>SENSE</sub> AND DCR SENSING

For applications requiring the highest possible efficiency at high load currents, a sense resistor would sacrifice several percentage points of efficiency compared to DCR sensing. Inductor DCR is a manifestation of the inductor's copper winding resistance. In high current applications, typical inductance values are low, allowing for a high saturation current inductor with sub 1mΩ DCR values. DCR current sensing takes advantage of this by sensing the voltage drop across the low copper DCR to monitor the inductor current. This eliminates the sense resistor and its additional power loss, thus increasing efficiency as well as lowering solution size and cost. An example of a DCR sensing application is shown in Figure 1. Figure 2 shows an efficiency comparison.

## MULTIPHASE OPERATION

The LTC3865 operates both of channels 180° out-of-phase. This reduces the required input capacitance and power supply induced noise. With its current mode architecture, it can be configured for dual outputs, or for one output with both power stages tied together.

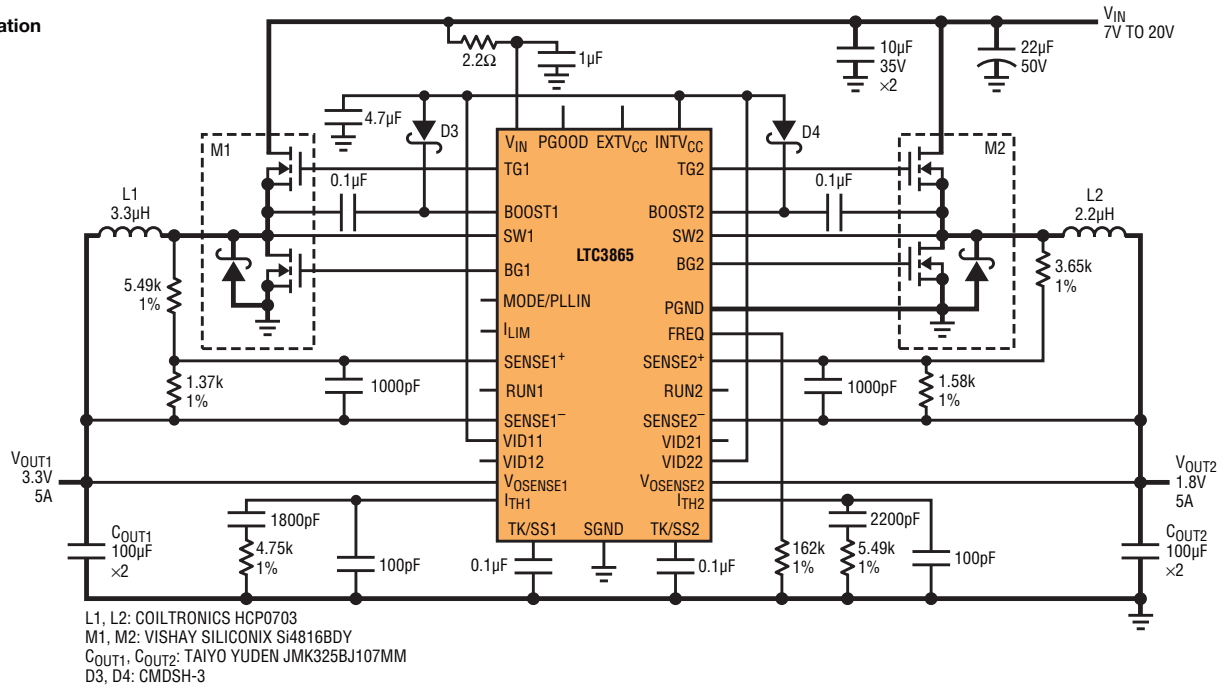
A dual-phase single output application is easy to configure; just tie the channels' compensation (ITH), feedback (V<sub>FB</sub>),

Table 1. Programming the Output Voltages

VID11/VID21	VID21/VID22	V <sub>OUT1</sub> /V <sub>OUT2</sub> (V)
INTV <sub>CC</sub>	INTV <sub>CC</sub>	5.0
INTV <sub>CC</sub>	Float	3.3
INTV <sub>CC</sub>	GND	2.5
Float	INTV <sub>CC</sub>	1.8
Float	Float	0.6 or External Divider
Float	GND	1.5
GND	INTV <sub>CC</sub>	1.2
GND	Float	1.0
GND	GND	1.1

The LTC3865 step-down regulator is ideal for applications requiring inductor DCR sensing for maximum efficiency under heavy load.

Figure 1. DCR sensing application



enable (RUN), power good (PGOOD) and track/soft-start (TRK/SS) pins together. By doubling the effective switching frequency and interleaving phases, the single output configuration minimizes the required input and output capacitance and voltage ripple, and allows for a fast transient response and increased current capability. An example for a dual-phase single output application is shown in Figure 3.

### OUTPUT OVERVOLTAGE PROTECTION WITH A NEGATIVE REVERSE CURRENT LIMIT

The traditional way of protecting an IC against overvoltage conditions is to use an overvoltage comparator, which guards against transient overshoots (>10%) as well as other more serious conditions that

may cause the output voltage to overshoot. In such cases, the top MOSFET is turned off and the bottom MOSFET is turned on and kept on until excessive energy has been

discharged from the output capacitor, bringing the output back to regulation.

One problem with turning on the bottom MOSFET indefinitely to clear an overvoltage condition is that sometimes excessive reverse current is required to discharge the output capacitor. In these cases the bottom FET experiences extreme current stress. To avoid this scenario, the LTC3865 adds a -53mV of reverse current limit. By setting a floor on how much reverse current is allowed, the LTC3865 limits how long the bottom FET can be turned on. This feature is important in applications that reprogram output voltages on the fly. For example, if the output voltage is changed from 1.8V to 1.5V, the reverse current limit is activated as shown in the Figure 4.

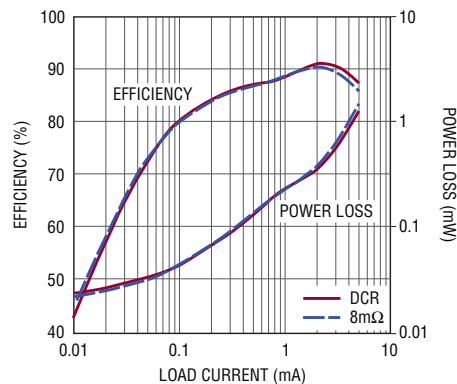


Figure 2. Efficiency for the circuit in Figure 1

The LTC3865's VID programmable output voltage decreases parts count while increasing design flexibility.

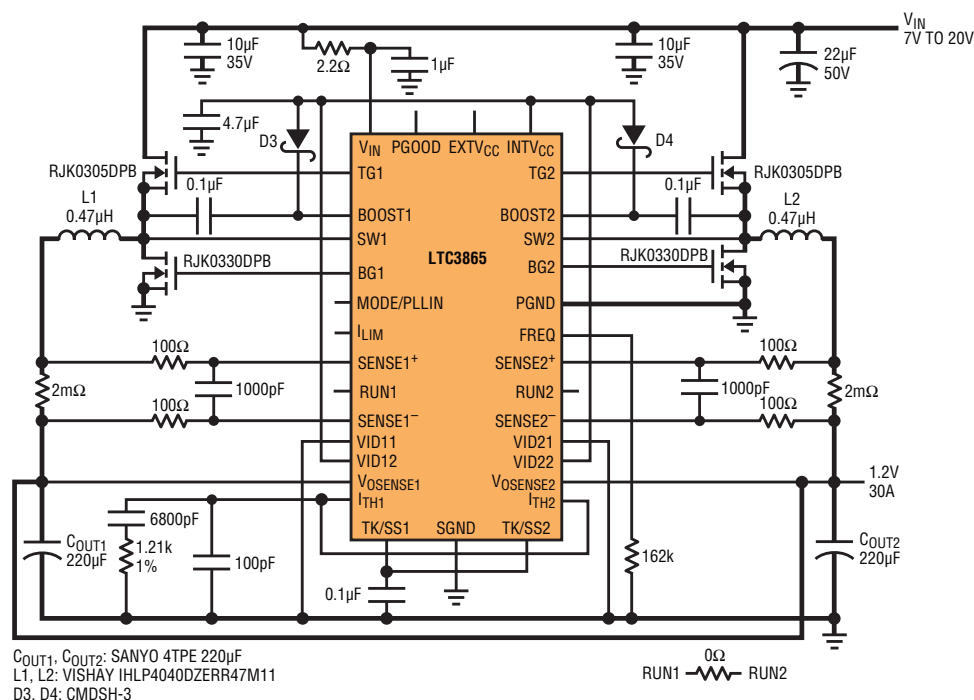


Figure 3. Single output application

## FREQUENCY SELECTION AND MODE/PLLIN

To maximize efficiency at light loads, the LTC3865 can be set for automatic Burst Mode® operation. Alternately, to minimize noise at the expense of light load efficiency, it can be set to operate in forced continuous conduction mode. For both relatively high efficiency and low noise operation, it can be set to operate with a hybrid of the two, namely pulse-skipping mode. Pulse-skipping mode, like forced continuous mode, exhibits lower output ripple as well as low audio noise and reduced RF interference as compared to Burst Mode operation. It also improves light load efficiency, but not as much as Burst Mode operation.

A clock on the MODE/PLLIN pin forces the controller into forced continuous mode and synchronizes the internal oscillator with the clock on this pin. The phase-locked loop integrated at this pin is composed of an internal voltage-controlled oscillator and a phase detector. This allows the turn-on of the top MOSFET of controller 1 to be locked to the rising edge of an external clock signal applied to the MODE/PLLIN pin. The frequency range for the LTC3865 is from 250kHz to 750kHz. If no external synchronization signal is applied, there is a precision 7.5µA current flow out of the FREQ pin that can be used to program the operating frequency of the LTC3865 from 250kHz to 750kHz through a single resistor from the pin to SGND.

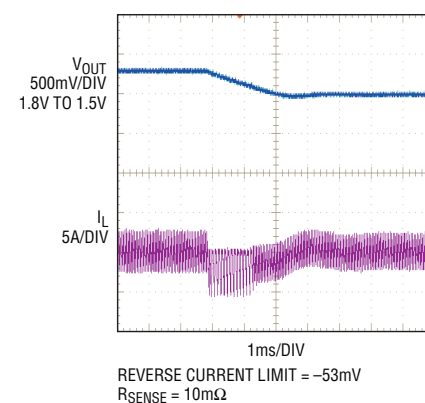


Figure 4. As  $V_{OUT}$  transitions from 1.8V to 1.5V, with  $-53\text{mV}$  reverse current limit and  $10\text{m}\Omega$  sense resistor, the reverse inductor current is limited at around 5.3A.

## CONCLUSION

The LTC3865 step-down regulator is ideal for applications requiring inductor DCR sensing for maximum efficiency under heavy load. It can regulate two separate outputs and can be configured for higher load current capability by tying its channels together, and/or by paralleling additional LTC3865 power stages. The LTC3865's VID programmable output voltage decreases parts count while increasing design flexibility. These features, along with its additional negative reverse current limit and integrated PLL features, make the LTC3865 an easy fit in a wide variety of applications. ■

# Tiny, Accurate Battery Gas Gauges with Easy-to-Use I<sup>2</sup>C Interface and Optional Integrated Precision Sense Resistors

Christoph Schwoerer, Axel Klein and Bernhard Engl

Imagine your daughter is catching her first wave on a surfboard and your video camera shuts down because the battery—reading half full when you started filming a few minutes ago—is suddenly empty. The problem is inaccurate battery gas gauging. Inaccurate fuel gauging is a common nuisance as many portable devices derive remaining battery capacity directly from battery voltage. This method is cheap but inaccurate since the relationship between battery voltage and capacity has a complex dependency on temperature, load conditions and usage history.

More accurate battery gauging can be achieved by monitoring not only the battery voltage but also by tracking the charge that goes in and out of the battery. For applications requiring accurate battery gas gauging, the LTC2941 and LTC2942 coulomb counters are tiny and easy-to-use solutions. These feature-rich devices are small and integrated enough to fit easily into the latest handheld gadgets.

The LTC2941 is a battery gas gauge device designed for use with single Li-Ion cells and other battery types with terminal voltages between 2.7V and 5.5V. A precision coulomb counter integrates current through a sense resistor between the battery's positive terminal and the load or charger. The high side sense resistor avoids splitting the ground path in the application. The state of charge is continuously updated in an accumulated charge register (ACR) that can be read out via an SMBUS/I<sup>2</sup>C interface. The LTC2941 also features programmable high and low thresholds for accumulated charge. If a threshold is exceeded, the device

communicates an alert using either the SMBUS alert protocol or by setting a flag in the internal status register.

The LTC2942 adds an ADC to the coulomb counter functionality of the LTC2941. The ADC measures battery voltage and chip temperature and provides programmable thresholds for these quantities as well.

The LTC2941 and LTC2942 are pin compatible and come in tiny 6-pin 2mm × 3mm DFN packages. Each consumes only 75µA in normal operation. Figure 1 shows the LTC2942 monitoring the charge status of a single cell Li-Ion battery.

## ANALOG INTEGRATOR ALLOWS PRECISE COULOMB COUNTING

Charge is the time integral of current. The LTC2941 and LTC2942 use a continuous time *analog* integrator to determine charge from the voltage drop developed across the sense resistor  $R_{SENSE}$  as shown in Figure 2.

The differential voltage between SENSE<sup>+</sup> and SENSE<sup>-</sup> is applied to an autozeroed differential integrator to convert the measured current to charge, as shown in Figure 2. When the integrator output ramps to REFHI or REFLO levels, switches S1, S2, S3 and S4 toggle to reverse the ramp direction. By observing the condition of the switches and the ramp direction, polarity is determined. A programmable prescaler adjusts integration time to match the capacity of the battery. At each underflow or overflow of the prescaler, the ACR value is incremented or decremented one count. The value of accumulated charge is read via the I<sup>2</sup>C interface.

The use of an analog integrator distinguishes the LTC coulomb counters from most other gas gauges available on the

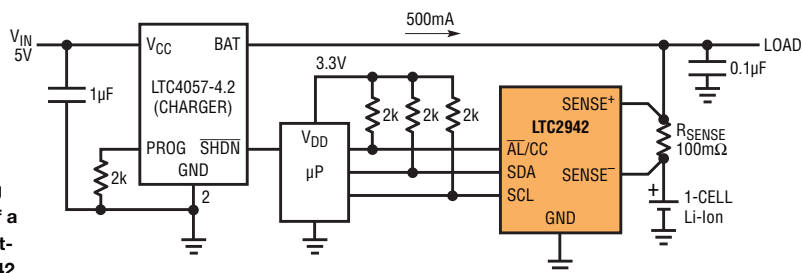
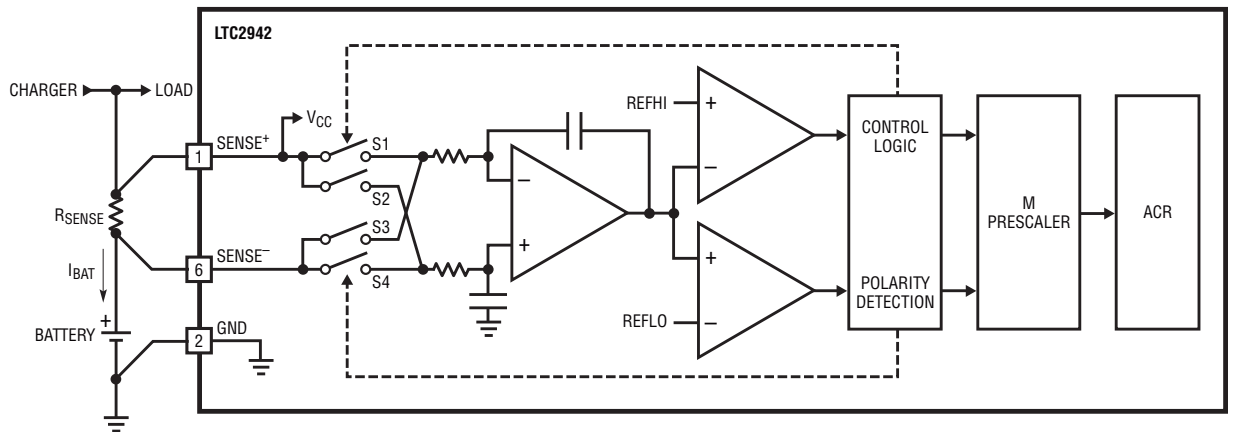


Figure 1. Monitoring the charge status of a single-cell Li-Ion battery with the LTC2942

Figure 2. Coulomb counter section of LTC2942



market. It is common to use an ADC to periodically sample the voltage drop over the sense resistor and digitally integrate the sampled values over time. This implementation has two major drawbacks. First, any current spikes occurring in-between sampling instants is lost, which leads to rather poor accuracy—especially in applications with pulsed loads. Second, the digital integration limits the precision to the accuracy of the available time base—typically low if not provided by additional external components.

In contrast, the coulomb counter of the LTC2941 and LTC2942 achieves an accuracy of better than 1% over a wide range of input signals, battery voltages and temperatures without such external components, as shown in Figures 3 and 4.

### INTEGRATED SENSE RESISTOR VERSIONS LTC2941-1 AND LTC2942-1

The accuracy of the charge monitoring depends not only on the accuracy of the chosen battery gas gauge but also on the precision of the sense resistor. The LTC2941-1 and LTC2942-1 remove the need for a high precision external resistor by including an internal, factory trimmed 50mΩ sense resistor. Proprietary internal circuitry compensates the temperature coefficient of the integrated metal resistor to a residual error of only 50ppm/°C which makes the LTC2941-1 and LTC2942-1 by far the most precise internal sense resistor battery gas gauges available today.

### TEMPERATURE AND VOLTAGE MEASUREMENT

The LTC2942 includes a 14-bit No Latency ΔΣ™ analog-to-digital converter with internal clock and voltage reference circuits to measure battery voltage. The integrated reference circuit has a temperature coefficient typically less than 20ppm/°C, giving an ADC gain error of less than 0.3% from -45°C to 85°C (see Figure 5). The inte-

gral nonlinearity of the ADC is typically below 0.5LSB as shown in Figure 6.

The ADC is also used to read the output of the on-chip temperature sensor. The sensor generates a voltage proportional to temperature with a slope of 2.5mV/°C, resulting in a voltage of 750mV at 27°C. The total temperature error is typically below ±2°C as shown in Figure 7.

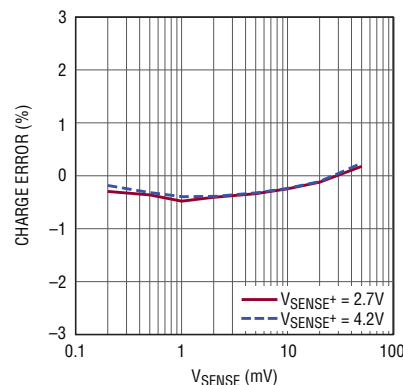


Figure 3. Charge error vs V<sub>SENSE</sub>

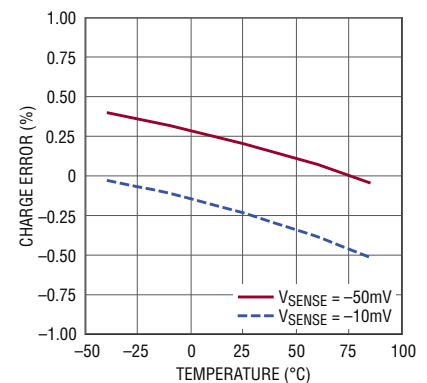


Figure 4. Charge error vs temperature

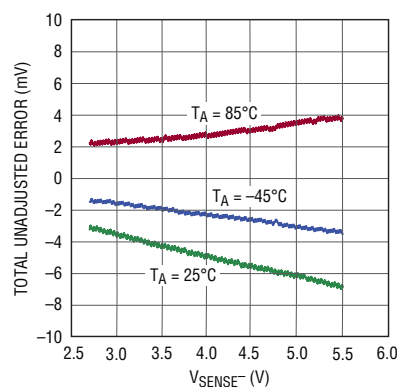


Figure 5. ADC total unadjusted error

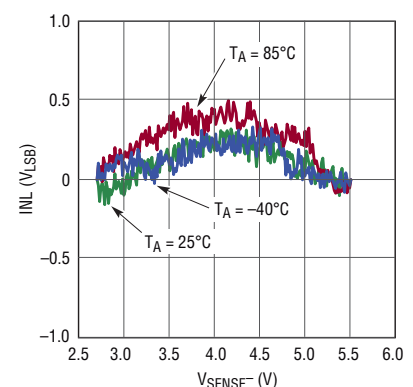


Figure 6. ADC integrated nonlinearity

Conversion of either temperature or voltage is triggered by setting the control register via the I<sup>2</sup>C interface. The LTC2942 also features an optional automatic mode where a voltage and a temperature conversion are executed once a second. At the end of each conversion the corresponding registers are updated before the converter goes to sleep to minimize quiescent current. Figure 8 shows a block diagram of the LTC2942, with the coulomb counter and its ACR, the temperature sensor, the ADC with the corresponding data registers and the I<sup>2</sup>C interface.

### USB CHARGING

Figure 9 shows a portable application designed to charge a Li-Ion battery from a USB connection. The LTC2942-1 monitors the charge status of a single-cell Li-Ion battery in combination with the LTC4088-1 high efficiency battery charger/USB power manager.

Once a charge cycle is completed, the LTC4088-1 releases the CHRG pin. The microcontroller detects this and sets the accumulated charge register to full either by writing it via the I<sup>2</sup>C interface or by applying a pulse to the charge complete ( $\overline{AL}/CC$ ) pin of the LTC2942-1 (if it is configured as input). Once initialized, the LTC2942-1 accurately monitors the

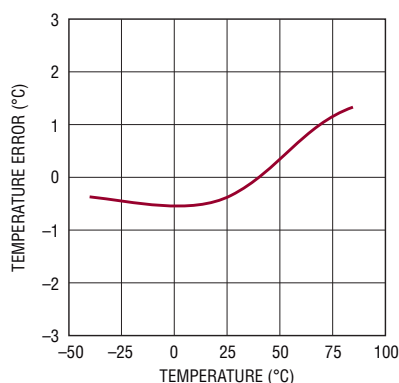


Figure 7. Temperature sensor error

charge flowing in and out of the battery, and the microcontroller can monitor the state of charge by reading the accumulated charge register via the I<sup>2</sup>C interface.

### ENERGY MONITORING

Real time energy monitoring is increasingly used in non-portable, wall powered systems such as servers or networking equipment. The LTC2941 and LTC2942 are just as well suited to monitor energy flow in any 3.3V or 5V rail application as they are in battery powered applications. Figure 10 shows an example.

With a constant supply voltage, the charge flowing through the sense resistor is proportional to the energy consumed by the load. Thus several LTC2941 devices can help determine exactly where system energy is consumed.

### MONITORING BATTERY STACKS

The LTC2941 and LTC2942 are not restricted to single cell Li-Ion applications. They can also monitor the charge state of a battery stack as shown in Figure 11.

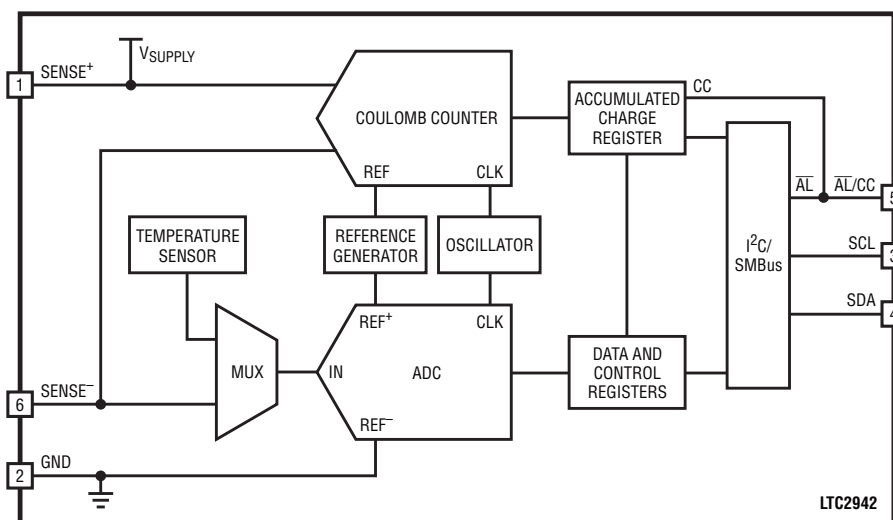
In this configuration, the power consumption of the gas gauge might lead to an unacceptable imbalance between the lower and the upper Li-Ion cells in the stack. This imbalance can be eliminated by supervising every cell individually, as shown in Figure 12.

By monitoring each cell's state of charge, the LTC2942-1 provides enough information to balance the cells while charging and discharging.

### TRACKING BATTERY CAPACITY WITH TEMPERATURE AND AGING

Battery capacity varies with temperature and aging. There is a wide variety of approaches and algorithms to track the battery capacity tailored to specific applications and the chemistry of the battery. The LTC2942 measures all physical quantities—charge, voltage, temperature and (by differentiating charge) current—necessary to model the effects of temperature and aging on battery capacity. The measured quantities are easily accessible by reading the corresponding registers with standard

Figure 8. Block diagram of the LTC2942



I<sup>2</sup>C commands. No special instruction language or programming is required.

The LTC2941 and LTC2942 do not impose a particular approach or algorithm to determine battery capacity from the measured quantities, but instead allow the system designer to implement algorithms tailored to the special needs of the system via the host controller. The microcontroller can then simply adapt the charge thresholds of LTC2941 and LTC2942 based on these calculations.

**CONCLUSION**

Battery gas gauging is one feature that lags behind other technological improvements in many portable electronics. The LTC2941 and LTC2942 integrated coulomb counters solve this problem with accurate battery gas gauging that is easy to implement and fit into the latest portable applications. For high accuracy in the tightest spots, the LTC2941-1 and LTC2942-1 versions integrate factory trimmed and temperature compensated sense resistors for the ultimate small coulomb counters. This new family of accurate coulomb counters can help prevent you from ever again missing those priceless vacation moments due to inaccurate battery charge monitoring. ■

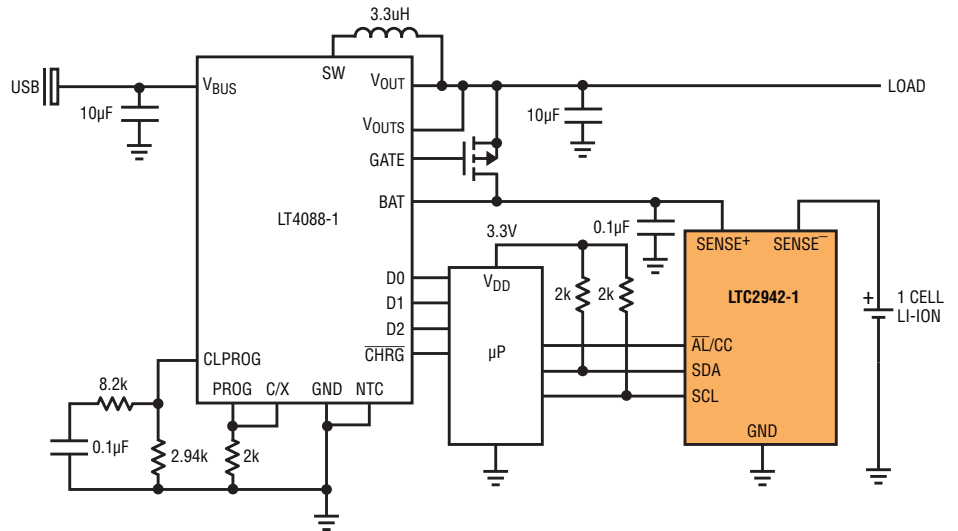


Figure 9. Battery gas gauge with USB charger

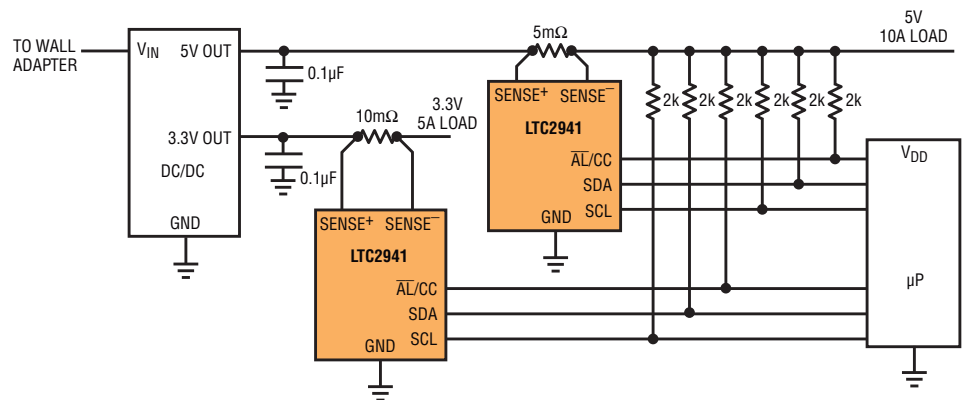


Figure 10. Monitoring system energy flow using LTC2941s at the loads

Figure 11. Using the LTC2942 in a battery stack

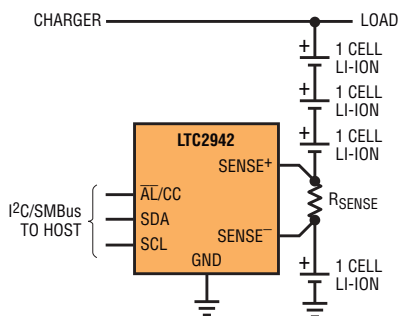
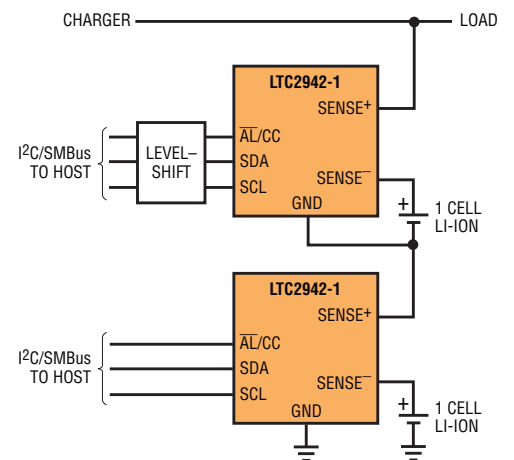


Figure 12. Individual cell monitoring of a 2-cell stack



# 140W Monolithic Switching Regulator Simplifies Constant-Current/Constant-Voltage Regulation

Eric Young

The LT3956 is a monolithic switching regulator that can generate constant-current/constant-voltage outputs in buck, boost or SEPIC topologies over a wide range of input and output voltages. With input and output voltages of up to 80V, a rugged internal 84V switch and high efficiency operation, the LT3956 can easily produce high power in a small footprint.

The LT<sup>®</sup>3956 combines key amplifier and comparator blocks with a high current/high voltage switching regulator in a tiny 5mm × 6mm package. See Figure 1 for an example of how little board space is needed to produce a complete constant-current, constant-voltage boost circuit ideal for LED driving, supercap charging or other high power applications that require the added protection of input or output current limiting.

## WHAT MAKES THE LT3956 TICK?

The big mover in the LT3956 is an 84V-rated, 90mΩ low side N-MOSFET switch with an internally programmed current limit of 3.9A (typ). The switching regulator can be powered from a supply as high as 80V because the N-MOSFET switch driver, the PWMOUT pin driver, and most internal loads are powered by an internal LDO linear regulator that converts  $V_{IN}$  to 7.15V, provided the  $V_{IN}$  supply is high enough. The switch duty cycle and current is controlled by a current-mode pulse-width modulator—an architecture that provides fast transient response, fixed switching frequency operation and an easily stabilized feedback loop at variable inputs and outputs. The switching frequency can be programmed from 100kHz to 1MHz with an external resistor, which allows designers to optimize component

size and performance parameters, such as min/max duty cycle and efficiency.

And at the heart of the LT3956 is a dual input feedback transconductance ( $g_m$ ) amplifier that combines a differential constant current sense with a standard low side voltage feedback. The handoff between these two loops is seamless and predictable. The feedback loop operating closest to its set point is auto-selected to be the loop controlling the flow of charge onto the compensation R-C network attached to the  $V_C$  pin. The voltage

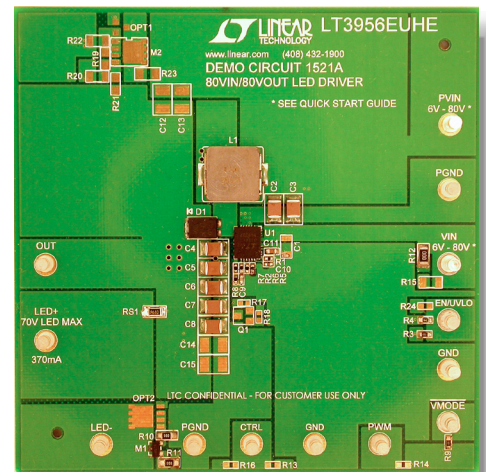


Figure 1. Complete high power, constant current, constant voltage boost circuit

level at the  $V_C$  pin in turn controls the current and duty ratio of the switch. A more thorough description of operation can be found in the LT3956 data sheet.

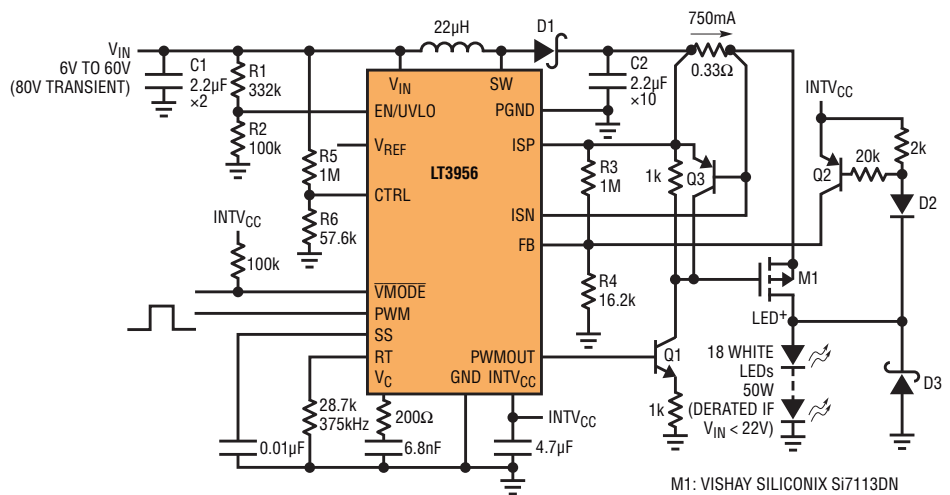


Figure 2. This 50W boost LED driver provides wide input range, PWM dimming and LED fault protection and reporting.

- M1: VISHAY SILICONIX Si7113DN
- D1: DIODES INC PDS5100
- L1: COILTRONICS DR125-220
- C1,C2: MURATA GRM42-2X7R225
- Q1: ZETEX FMMT497
- Q2,Q3: ZETEX FMMT589
- D2: BAV116W
- D3: DIODES INC B1100/B



The big mover in the LT3956 is an 84V-rated, 90mΩ low side N-MOSFET switch with an internally programmed current limit of 3.9A (typ). The switching regulator can be powered from a supply as high as 80V because the N-MOSFET switch driver, the PWMOUT pin driver, and most internal loads are powered by an internal LDO linear regulator that converts  $V_{IN}$  to 7.15V.

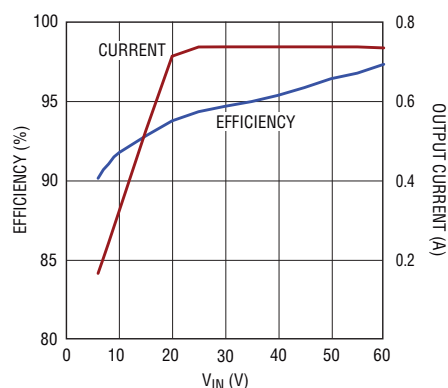


Figure 3. High 94% efficiency means less than 3W dissipation in the converter shown in Figure 2.

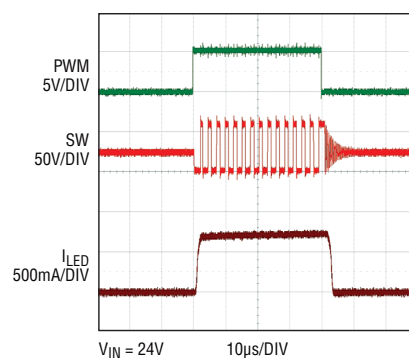


Figure 4. Boost PWM dimming waveforms for 60V of LEDs shows microsecond rise and fall times and excellent constant current regulation even over short intervals.

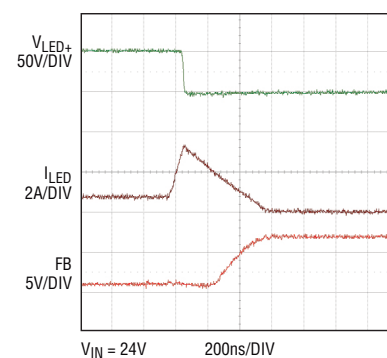


Figure 5. LED+ terminal of boost shorted to GND is prevented from damaging switching components by a novel circuit.

## A RUGGED HIGH POWER BOOST LED DRIVER

Figure 2 shows a 50W boost LED driver that operates from a 24V input, showing off some of the unique capabilities of this product when applied as an LED driver. This boost circuit tolerates a wide input range—from 6V to 60V. At the low end of this  $V_{IN}$  range, the circuit is prevented from operating too close to switch current limit by scaling back the programmed LED current as  $V_{IN}$  declines—set by the resistor divider ( $R_5$  and  $R_6$ ) on the CTRL pin. Figure 3 shows efficiency and LED current versus  $V_{IN}$ . The high efficiency (94%) means passive cooling of the regulator is adequate for all but the most extreme environmental conditions.

## ANALOG AND PWM LED DIMMING

The LT3956 offers two high performance dimming methods: analog dimming via the CTRL pin and the ISP/ISN current sense inputs, and PWM dimming through the PWM input and PWMOUT output.

### Analog Dimming

Analog dimming is achieved via the voltage at the CTRL pin. When the CTRL pin is below 1.2V, it programs the current sense threshold from zero to 250mV (typ) with guaranteed accuracy of  $\pm 3.5\%$  at 100mV. When CTRL is above 1.2V, the current sense threshold is fixed at 250mV. At CTRL = 100mV (typ), the current sense threshold is set to zero. This built-in offset is important to the feature if the CTRL pin is driven by a resistor divider—a zero programmed current can be reached with a non-zero CTRL voltage. The CTRL pin is high impedance so it can be driven in a wide variety of configurations.

### PWM Dimming

Pulse width modulation (PWM) of LED current is the preferred technique to achieve wide range dimming of the light output. Figure 2 shows a level shift transistor Q1 driving a high side disconnect P-MOSFET M1. This configuration allows PWM dimming with a single wire

solution for the luminary—the LED cathode current can return on a common GND. A scope photo of PWM dimming waveform (Figure 4) shows sharp rise and fall times, less than 200ns, and quick stabilization of the current. Although a low side N-MOSFET disconnect at the cathode is the simpler and more obvious (and a bit faster) implementation for this particular boost circuit using the LT3956, the use of high side PWM disconnect is important to a boost protection strategy to be discussed below.

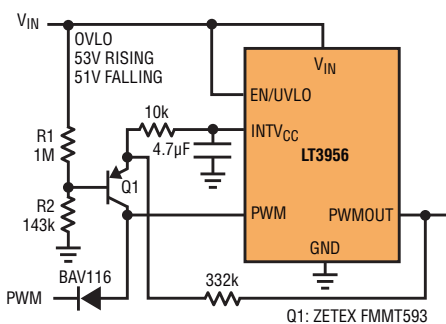
## CONSIDERATIONS FOR PROTECTING THE LED, THE DRIVER, AND THE INPUT POWER SUPPLY

LED systems often require load fault detection. Limiting the output voltage in the case of an open LED string has always been a basic requirement and is achieved through a resistor divider ( $R_3$  and  $R_4$ ) at the FB input. If the string opens, the switching regulator regulates  $V_{FB}$  to a constant 1.25V (typ). In addition to the  $g_m$  amplifier that provides this constant

voltage regulation, the FB input also has two fixed setpoint comparators associated with it. The lower setpoint comparator activates the  $\overline{V_{MODE}}$  open collector pull-down when FB exceeds 1.20V (typ). After the disconnection of the LED and loss of the current regulation signal, the output rises until it reaches the constant voltage regulation setpoint. During this voltage ramp the  $\overline{V_{MODE}}$  pin asserts and holds, indicating that the LED load is open. This signal maintains its state when PWM goes low and the regulator stops switching, allowing for the likelihood that output voltage may fall below the threshold without an occasional refresh provided by switching. The  $\overline{V_{MODE}}$  pin quickly updates when PWM goes high. The  $\overline{V_{MODE}}$  signal can also indicate that the regulation mode is transitioning from constant current to constant voltage, which is the appropriate function for current limited constant voltage applications, such as battery chargers.

The boost circuit in Figure 2 uses the voltage feedback (FB) input in a unique fashion—protecting the LED<sup>+</sup> node from a fault to GND while preserving all the other desirable attributes of the LED driver. A standard boost circuit has a direct path from the supply to the output, and therefore cannot survive a GND fault on its output when the supply current is not limited. There are a number of situations where one might desire to protect the switching regulator from a short to GND of the LED anode—perhaps the luminary is separated from the driver circuit by a connector or by a long wire, and the input supply is a high capacity battery.

The LT3956 has a feature to provide this protection. The overvoltage FB (OVFB) comparator is a second comparator on the FB input with a setpoint higher than the  $V_{FB}$  regulation voltage. It causes the PWMOUT pin to transition low and switching to stop immediately when the FB input exceeds 1.31V(typ).



**Figure 6.  $V_{IN}$  overvoltage circuit halts switching and disconnects the load during high input voltage transients.**

The OVFB comparator can be used in an output GND fault protection scheme (patent pending) for the boost. The key elements are the high side LED disconnect P-MOSFET (M1) and its supporting driving circuit responsive to the PWMOUT signal, and the output GND fault sensing circuit consisting of D2, Q2 and two resistors that provide signal to the FB node. The circuit works by sensing the current flowing in D2 when the output is shorted, and thereby triggering the OVFB comparator. In response to the OVFB comparator, the high side switch M1 is maintained in an off-state and the switching is stopped until the fault condition is removed. Figure 5 shows the current waveform in the M1 switch during and output short circuit event.

#### Additional Considerations for Protecting the LED

Some harsh operating environments produce transients on the input power supply that can overdrive a boosted output, if only for a short while, and potentially damage the LEDs with excessive current.

To discontinue switching and disconnect the LEDs during such a transient, a simple add-on circuit to the PWM input, shown as a breakout in Figure 6, disconnects the LED string and idles the switcher when  $V_{IN}$  exceeds 50V. The circuit works by sourcing current to the PWM input of the LT3956 from the collector of Q1 when  $V_{IN}$  is low enough, but cutting off that current when the base of Q1 (set

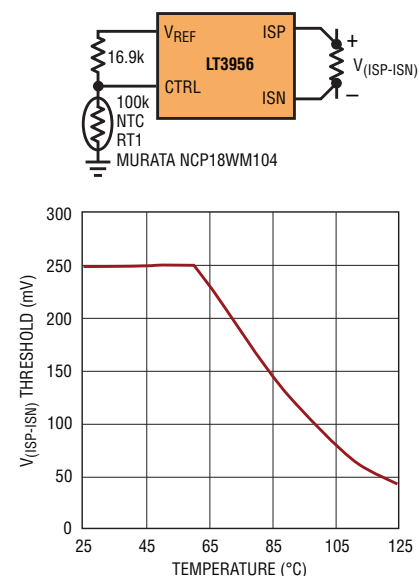
by the resistor divider from  $V_{IN}$ ) exceeds 6.5V (INTV<sub>CC</sub> minus a  $V_{BE}$ ). When PWM falls below its threshold, PWMOUT goes low as well. Hysteresis of ~2V is provided by PWMOUT. Because of the high PWM threshold (0.85V minimum over temperature), the blocking diode D1 can be added to preserve the PWM dimming capability.

The LT3956 provides solutions to thermal dissipation problems encountered driving LEDs. With high power comes the concern about reduced lifetime of the LED due to continuous operation at high temperatures. Increasing numbers of LED module applications implement thermal sensing for the LED, usually employing an NTC resistor coupled to the LED heat sink with thermal grease. A simple circuit employing the CTRL and  $V_{REF}$  pins of the LT3956 and an NTC resistor sensing the LED temperature produces a thermal derating curve for the LED current as shown in Figure 7.

#### A CONSTANT-CURRENT/VOLTAGE REGULATOR SERVES A WIDE RANGE OF APPLICATIONS

Driving LEDs makes excellent use of the LT3956 features, but it isn't the only application that requires constant

**Figure 7. CTRL and  $V_{REF}$  pins provide thermal derating to enhance LED reliability.**



voltage at constant current. It can be used for charging batteries and supercapacitors, or driving a current source load such as a thermoelectric cooler, just to name a few examples. It can be used as a voltage regulator with current limited input or output, or a current regulator with a voltage clamp.

Pursuing this line of thinking, Figure 8 shows a SEPIC supercap charger that draws power from a fixed 24V input, and has an input current limit of 1.2A. The SEPIC architecture is chosen for several reasons: it can do both step-up and step-down, and it has inherent isolation of the input from the output. A coupled inductor is chosen over a 2-inductor approach because of the smaller, lower-cost circuit. The magnetic coupling effect allows the use of a single coupling capacitor and the switch current levels of the LT3956 make strategic use of the readily available coupled inductor offerings of major magnetics vendors.

A charging circuit for a large value capacitor (1F or more) might be found in a non-battery based backup power system. These chargers would draw power from some inductive based DC supply that operates

intermittently, but the available power might be limited based on an overall system budget. The output charging rate of the circuit of Figure 8 is not based on any timer, but rather on the output voltage level as sensed by the CTRL pin. Below a certain output voltage, 22V in this case, the input current is limited so that the switching regulator is maintained within its own current limit. At higher output voltages, the default internal current sensing threshold of 250mV (typ) establishes that the input current cannot exceed 1.2A, and so the output current drops. At very low output voltages less than 1.5V, the network driving the SS pin of LT3956 reduces the switching frequency and the current limit to maintain good control of the charging current. When the load is within 5% of its target voltage, the  $\overline{\text{VMODE}}$  pin toggles to indicate the end of constant current mode and entry into constant voltage regulation.

This circuit is intended for a situation where  $V_{IN}$  does not experience much variation during normal operation. The design procedure for this type circuit begins with setting the maximum input current limit with the  $R_{SENSE}$  value and the 250mV default threshold. The next design step is to determine the  $V_{OUT}$  level below

which  $V_{IN}$  current is to be reduced through CTRL to maintain less than 2.5A average switching current. Assuming slightly less than 90% efficiency, set the resistor divider  $R_5$  and  $R_6$  to give CTRL = 1.1V when

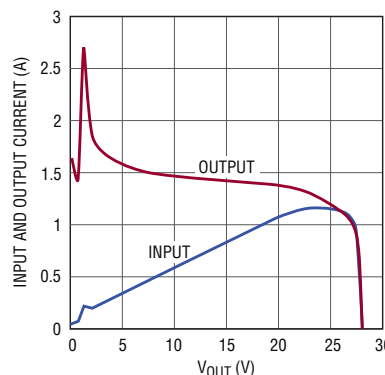
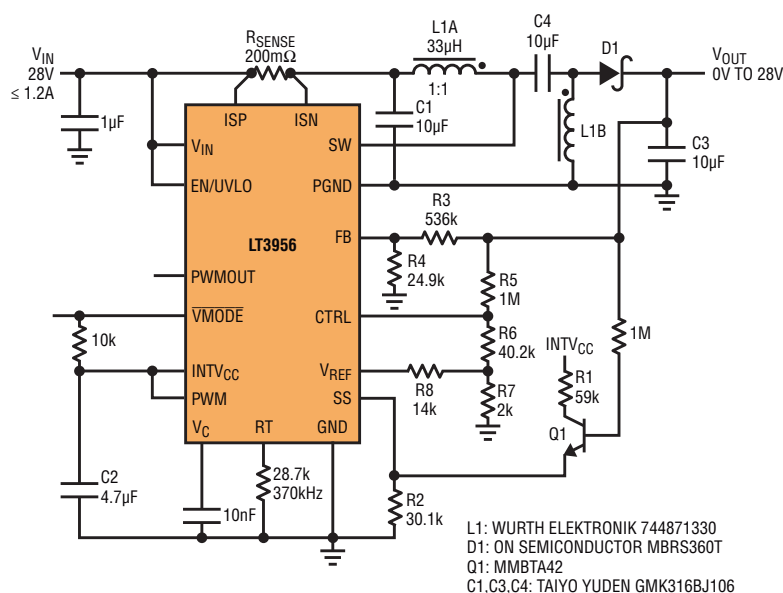
$$V_{OUT} = \frac{V_{IN} \cdot 0.9 \cdot I_{IN(MAX)}}{2.5A - I_{IN(MAX)}}, \text{ at CTRL} = 1.1V$$

The values of  $R_5$  and  $R_6$  should be an order of magnitude higher value than resistor  $R_7$ . The resistor divider  $R_7$  and  $R_8$  is set to provide a minimum voltage at CTRL, greater than 125mV, which is needed to set non-zero value for input current.

### CONCLUSION

The LT3956 simplifies power conversion applications needing both constant-current and constant-voltage regulation, especially if they are constrained by board area and/or bill-of-materials length. Its features are selected to minimize the number of external analog blocks for these types of applications while maintaining flexibility. Careful integration of these components into the switching regulator makes it possible to easily produce applications that would otherwise require a cumbersome combination of numerous externals. ■

Figure 8. Supercapacitor charger with current limited input provides controlled charging current over a wide output range.



# 2MHz Dual Buck Regulator Operates Outside of AM Radio Band When Delivering 3.3V and 1.8V from 16V Input

Pit-Leong Wong

The number of microprocessor-based control units continues to grow in both automobiles and industrial systems. Because the amount of required processing power is also increasing, even modest processors require a low voltage core supply in addition to 3.3V or 5V memory, I/O and analog supplies.

In automotive systems, power comes from the battery, with its voltage typically between 9V and 16V. Including cold crank and double battery jump-starts, the minimum input voltage may be as low as 4V and the maximum up to 36V, with even higher transient voltages. Likewise, a 24V industrial supply may be as high as 32V. With these high input voltages, linear regulators cannot be used for supply currents greater than 200mA without overheating the regulator. Instead, high efficiency switching regulators must be used to minimize thermal dissipation.

There are challenges in applying switching regulators in these systems. A small circuit is desired, and certain operating frequencies may be unacceptable. At high step-down ratios, switching regulators typically operate at frequencies in the AM radio band. One solution is to dynamically move the power converter switching frequency (and harmonics) away from the tuned AM frequency, but moving the switching frequency can lead to unexpected EMI problems.

A cleaner solution is to simply set the switching frequency higher than the top of the AM radio band, which is at 1.8MHz. This is easier said than done, since most existing buck converters cannot meet the low (<100ns over temperature) minimum

on-time required to produce the step-down ratio from a 16V input to a 3.3V output.

The LT3640 solves this problem with a fast non-synchronous high voltage buck converter and a high efficiency synchronous low voltage buck converter. With a typical minimum on time of about 60ns over temperature, the high voltage channel in the LT3640 can deliver 3.3V from 16V<sub>IN</sub> at 2MHz with comfortable margin. The synchronous low voltage channel in the LT3640 can be cascaded from the 3.3V channel to generate the other lower voltage buses such as 2.5V, 1.8V or 1.2V.

The LT3640 also includes a programmable power-on reset timer and watchdog

timer to supervise microprocessors.

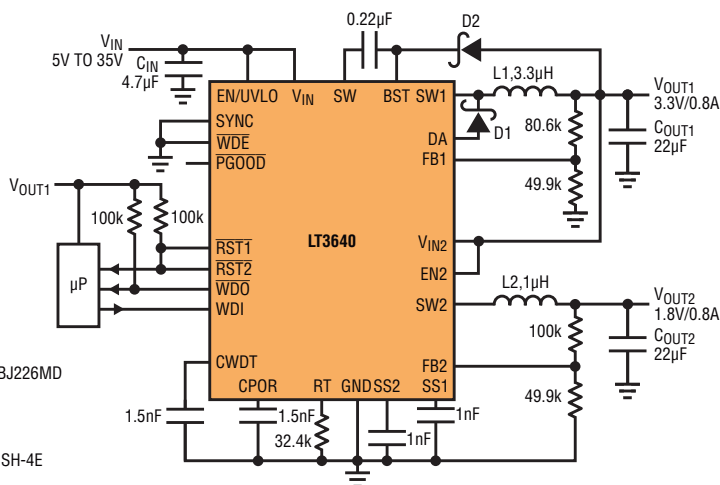
The LT3640 is offered in 4mm × 5mm QFN and 28-lead FE packages.

## DUAL BUCK REGULATOR

The LT3640 is a dual channel, constant frequency, current mode monolithic buck switching regulator with power-on reset and watchdog timer. Both channels are synchronized to a single oscillator with frequency set by R<sub>T</sub>. The adjustable frequency ranges from 350kHz to 2.5MHz. The internal oscillator of the LT3640 can be synchronized to an external clock signal on the SYNC pin.

The high voltage channel is a non-synchronous buck with an internal 1.7A NPN top switch that operates from an input of 4V to 35V. Above 35V, an internal overvoltage lockout circuit suspends switching, protecting the LT3640 and downstream circuits from input faults as high as 55V. The low voltage channel is a synchronous buck with internal CMOS power switches

**Figure 1. 2MHz 3.3V/0.8A and 1.8V/0.8A step-down regulators**



C<sub>IN</sub>: TAIYO YUDEN UMK316BJ475KL  
 C<sub>OUT1</sub>, C<sub>OUT2</sub>: TAIYO YUDEN JMK212BJ226MD  
 L1: VISHAY IHLP2020BZER3R3  
 L2: VISHAY IHLP1616BZER1R0  
 D1, D2: DIODES INC. B240A  
 D2: CENTRAL SEMICONDUCTOR CMDSH-4E

The high voltage buck regulator in the LT3640 has a very fast minimum on time of about 60ns. This enables the LT3640 to operate at a high step-down ratio while maintaining high switching frequency.

providing high efficiency without the need of an external Schottky diode and accepts an input of 2.5V to 5.5V. Typically, the low voltage channel can operate from the output of the high voltage channel to form a cascaded structure as shown in Figure 1, but it can also operate from a separate supply source. The low voltage channel only switches when the high voltage channel output is within regulation.

### FAST, HIGH VOLTAGE BUCK REGULATOR

The high voltage buck regulator in the LT3640 has a very fast minimum on time of about 60ns. This enables the LT3640 to operate at a high step down ratio while maintaining high switching frequency. Figure 3 shows the waveform of the LT3640 operating from input voltage of 35V to regulate a 3.3V output at 2MHz. The on time of the top power switch is about 60ns, which is also flat over temperature.

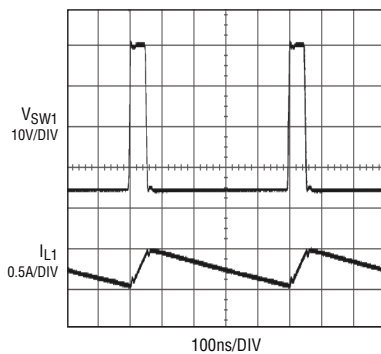


Figure 3. Fast high voltage buck regulator

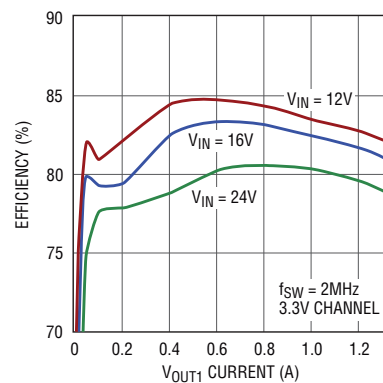
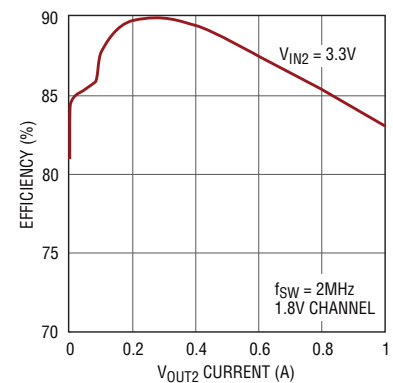


Figure 2. Efficiency of the circuit in Figure 1



Besides the fast minimum on time, the high voltage buck regulator has fast switching edges to minimize switching losses and improve conversion efficiency at high frequency. Figure 4 shows the efficiency of the high voltage buck regulator at 2MHz operation for different input voltages. For 5V output voltage, the high voltage buck maintains an efficiency of higher than 86% for input voltage up to 24V.

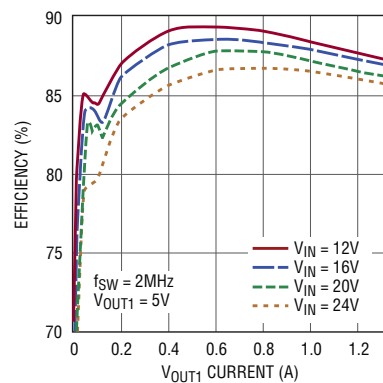


Figure 4. Efficiency of the high voltage buck regulator

### OUTPUT SHORT-CIRCUIT ROBUSTNESS

The LT3640 monitors the catch diode current to guarantee the output short-circuit robustness for the high voltage buck converter. The LT3640 waits for the catch diode current to fall below its limit before starting a new cycle. The top NPN does not turn on until the catch diode current is below its limit. This control scheme

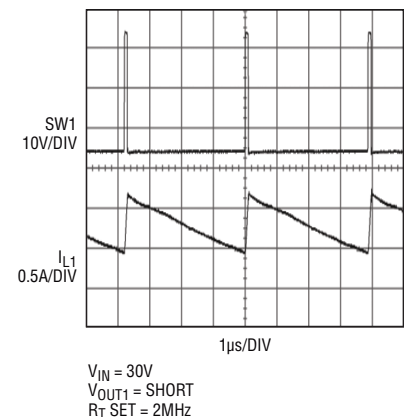


Figure 5. Output shorted robustness, high voltage channel

ensures cycle-by-cycle current limit, providing protection against shorted output. The switching waveform for  $V_{IN} = 30\text{V}$  and  $V_{OUT} = 0\text{V}$  is shown in Figure 5.

### LOW VOLTAGE SYNCHRONOUS BUCK REGULATORS

The low voltage channel is a synchronous buck with internal CMOS power switches providing high efficiency without the need of external Schottky diode. This channel only switches when the high voltage channel output is within regulation. The output can be programmed as low as 0.6V, covering any core voltage in modern microprocessors.

The low voltage buck has a similar scheme as the high voltage buck of monitoring the current in the bottom NMOS to guarantee shorted output robustness. However, when the bottom NMOS current exceeds its limit, the oscillator frequency is not affected. The low voltage buck simply skips one cycle to avoid interference with the high voltage buck.

At light load the low voltage buck also operates in low ripple Burst Mode operation to minimize output ripple and power loss. Although the two channels in the LT3640 share a common oscillator, they may require different light load operation frequencies to optimize efficiencies at their respective loads. In this case, the oscillator always runs at the higher frequency, with the channel requiring the lower frequency skipping cycles. Figures 6 and 7 show the light load switching waveforms of two channels running at same reduced frequency and at different frequencies, respectively. Output ripple for both channels remains below 10mV<sub>p-p</sub>. No-load quiescent current from the input is only 300μA with both outputs in regulation.

### BENEFITS OF CASCADING

As described above, there are clear advantages of cascading two switchers to generate I/O and core supplies. The higher operating frequency reduces circuit size

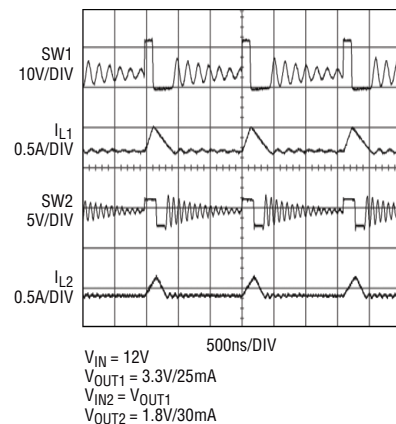


Figure 6. Two channels running in discontinuous mode at light load remain synchronized.

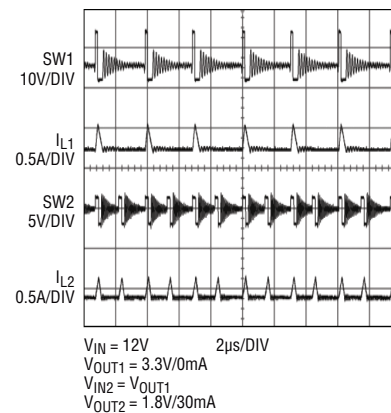


Figure 7. At still lighter loads, the two channels switch at different frequencies to maintain high efficiency and low output ripple.

and provides faster transient response for better regulation. The low voltage technology used for the core supply switcher further reduces solution size.

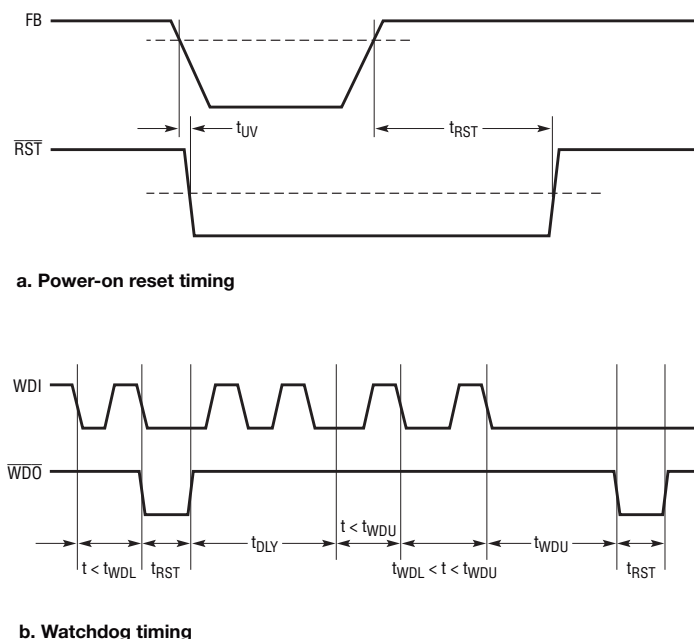
Although the core supply is generated via two conversions, with two efficiency hits, keep in mind that the core supply is often low power, even if it is high current, so total power loss is minimal. Also, a buck converter generating the core voltage directly from the input does not typically operate in an efficient region anyway, and it would be larger and slower. Comparing the circuit in

Figure 1 against two non-synchronous bucks operating from  $V_{IN}$ , the overall efficiency is nearly identical. If the core voltage is reduced from 1.8V to 1.2V, the LT3640 circuit is actually more efficient.

### POWER-ON RESET AND WATCHDOG TIMER

In high reliability systems, a supervisor monitors the activity of the microprocessor. If the processor appears to stop, due to either hardware or software faults, the supervisor resets the microprocessor in an attempt to restore the system to a functional state. While some

Figure 8. Power-on reset and watchdog timing



modern processors include internal supervisor functions, it is better practice to separate the two. Typical supervisor functions are voltage monitors with power-on resets to qualify supply voltages and watchdog timers to monitor software and hardware functions.

The LT3640 includes one power-on reset timer for each buck regulator and one common watchdog timer. Power-on reset and watchdog timers are both adjustable using external capacitors.

Once the high voltage buck output voltage reaches 90% of its regulation target, the high voltage channel reset timer is started and the  $\overline{RST1}$  pin is released after the reset timeout period. The low voltage channel reset timer is started once the low voltage buck output voltage reaches 92% of its regulation voltage, and releases  $\overline{RST2}$  after the reset timeout period.

The watchdog circuit monitors a microprocessor's activity. As soon as both  $\overline{RST1}$  and  $\overline{RST2}$  are released and an additional delay has expired, the watchdog starts monitoring the signal at the  $\overline{WDI}$  pin. The LT3640 implements windowed watchdog

function for higher reliability. If the falling edges on the  $\overline{WDI}$  pin are grouped too close together or too far apart, the  $\overline{WDO}$  pin is pulled down for a period the same as the power-on reset timeout period before the watchdog timer is started again. The timing diagrams of the power-on reset and watchdog timer are shown in Figure 8.

### LOW NOISE DATA ACQUISITION SUPPLY

Figure 9 shows a 4-output supply that generates low noise 5V and 3.3V rails for analog circuits, along with 3.3V I/O and 1.5V core supplies for digital circuits. The high voltage channel of the LT3640 converts the input to a 5.7V intermediate bus, the low voltage channel bucks to the 1.5V core, and a few LDOs regulate the 5V and 3.3V outputs. The 5.7V bus voltage gives the 5V regulator suitable headroom for good PSRR and transient performance.

Diode D2 performs two functions. First, it lowers the intermediate voltage to a value below the 5.5V maximum operating voltage of the synchronous buck regulator. Second, it isolates high frequency ripple current flowing into the  $V_{IN2}$  and

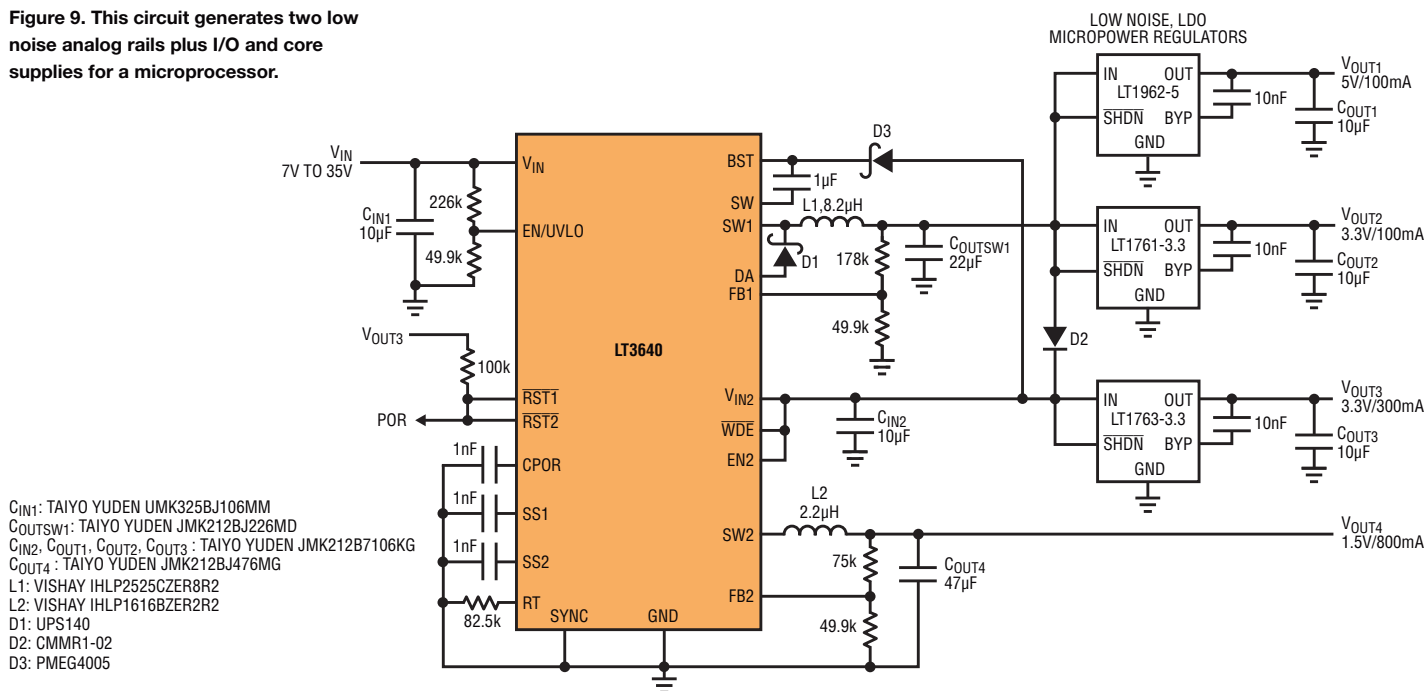
BST pins of the LT3640 from the inputs of the LDOs regulating the analog supplies, resulting in quiet analog rails.

Total current draw from the 5.7V rail is 820mA, so about 30% more power is available from this output.  $\overline{RST1}$  and  $\overline{RST2}$  indicate power is good when the 1.5V and 5.7V rails are in regulation. The watchdog function is not used here, and is disabled by tying  $\overline{WDE}$  to  $V_{IN2}$ . The associated pins, not shown on this schematic, should be left floating.

### CONCLUSION

The LT3640 is a dual channel buck regulator. The high voltage channel buck is capable of converting 16V input voltage to 3.3V output at 2MHz with comfortable margin. The high voltage buck maintains efficiency above 86% for delivering 5V from up to 24V input at 2MHz switching frequency. The low voltage channel buck input ranges from 2.5V to 5.5V. The LT3640 also includes power-on reset and watchdog timer to monitors a microprocessor's activity. The high frequency high efficient buck converters and the programmable timers make the LT3640 ideal for automotive applications. ■

Figure 9. This circuit generates two low noise analog rails plus I/O and core supplies for a microprocessor.



# Eight 16-Bit, Low INL, $V_{OUT}$ DACs in a 4mm × 5mm QFN Package: Unparalleled Density and Flexibility

Leo Chen

While 16-bit  $V_{OUT}$  DACs are not uncommon, the combination of low INL ( $\pm 4$  LSB) and high density (eight DACs in a 4mm × 5mm QFN package) allows the LTC2656 to fit an unparalleled range of sockets. Space-saving features also include a built-in 2ppm/°C reference, with performance typically reserved for external references. These characteristics, along with superior offset and gain error specifications, make the LTC2656 a powerful device housed in a tiny package.

Although the LTC2656 is a formidable standalone device, it can be readily combined with other Linear Technology products to produce uniquely high performance solutions.

## A DIGITALLY CONTROLLED POWER SUPPLY USING THE LT3080 1.1A REGULATOR

Another noteworthy product in the Linear Technology portfolio is the LT3080. The LT3080 is a 1.1A low dropout

linear regulator that can be paralleled to increase output current or spread heat on surface mounted boards. Typically the output voltage of the LT3080 is adjusted by a resistor at the SET pin of the part (Figure 1). A fixed current of 10 $\mu$ A flows out of the SET pin through the resistor and the resulting voltage drop programs the output of the regulator.

The LTC2656 can be combined with the LT3080 to create a digitally controlled

power supply. If the output of the DAC is connected to the SET pin of the regulator (Figure 2), the LT3080 acts as a unity gain buffer. The DAC simply sinks the 10 $\mu$ A from the internal current source and directly controls the output of the regulator creating a digitally controlled power supply. Should more than 1.1A be needed, multiple LT3080s can be paralleled to provide more output current.

The LTC2656's 16 bits of resolution yield finer tuning of the LT3080's output than that of a digital potentiometer. Typical digital potentiometers have resolutions of only 8 bits; high resolution digital pots are at 10 bits. The  $\pm 4$  LSB INL of the LTC2656 is far superior to the INL of typical digital pots. The LTC2656-L combined with an LT3080 results in a power-supply with an adjustable range of 0V–2.5V, while using the LTC2656-H produces a power supply with an adjustable range of 0V–4.096V.

Figure 1. Simple variable output voltage 1.1A supply

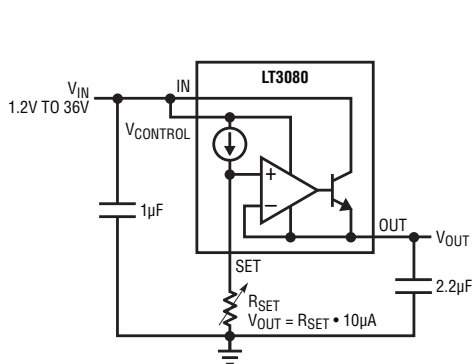
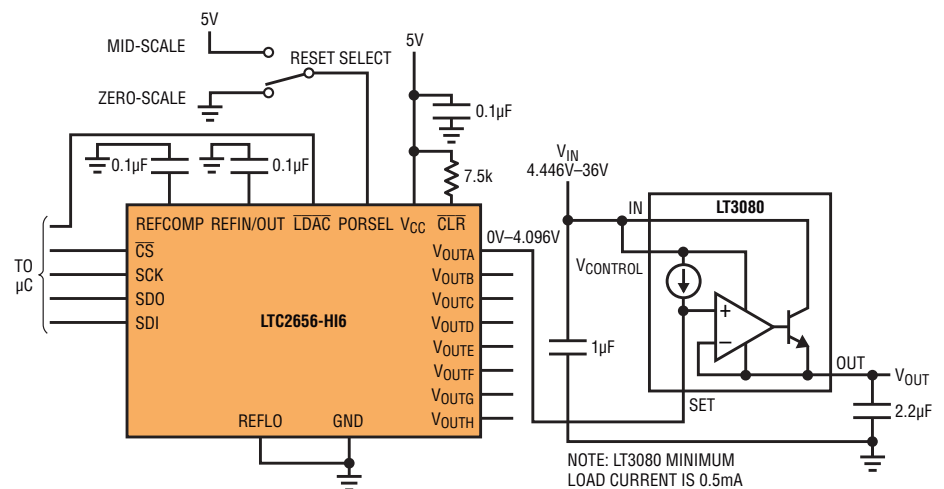


Figure 2. Digitally controlled version of the power supply in shown in Figure 1 with a 0V–4.096V output range. For a 0V–2.5V output range use the LTC2656-LI.





Although the LTC2656 is a formidable standalone device, it can be readily combined with other Linear Technology products to produce uniquely high performance solutions.

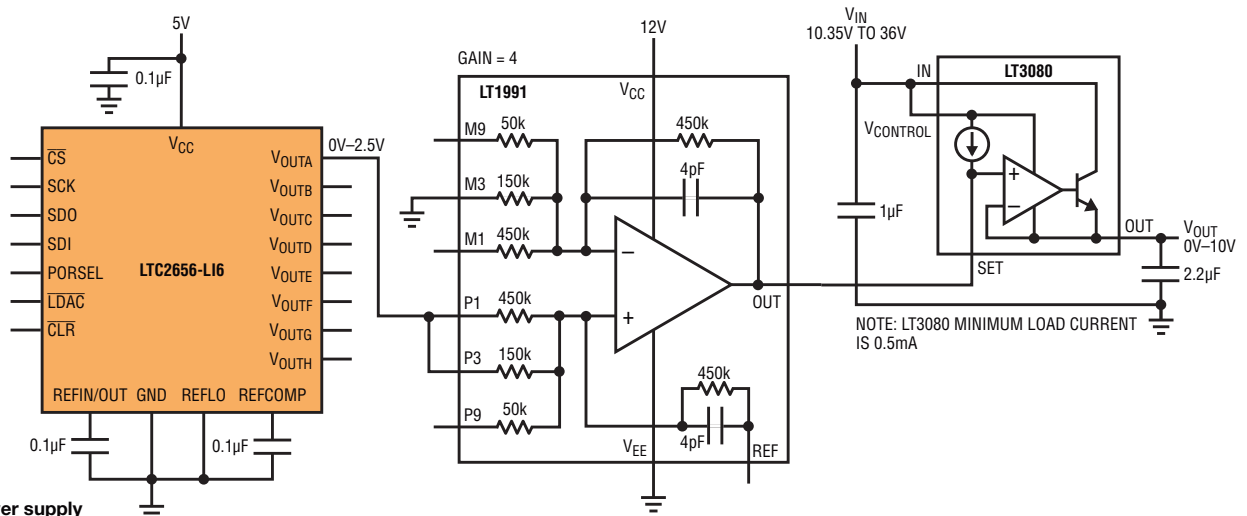


Figure 3. Expanding the power supply output range to 0V-10V

The two Linear Technology parts complement each other very well. The LT3080 has a max offset of 2mV in the DFN package, while the LTC2656 has a max offset of  $\pm 2$ mV. This means that there will only be a slight degradation in offset performance when combining these two parts. This circuit can also be easily replicated at

each of the DAC outputs in order to create an 8-channel adjustable power supply.

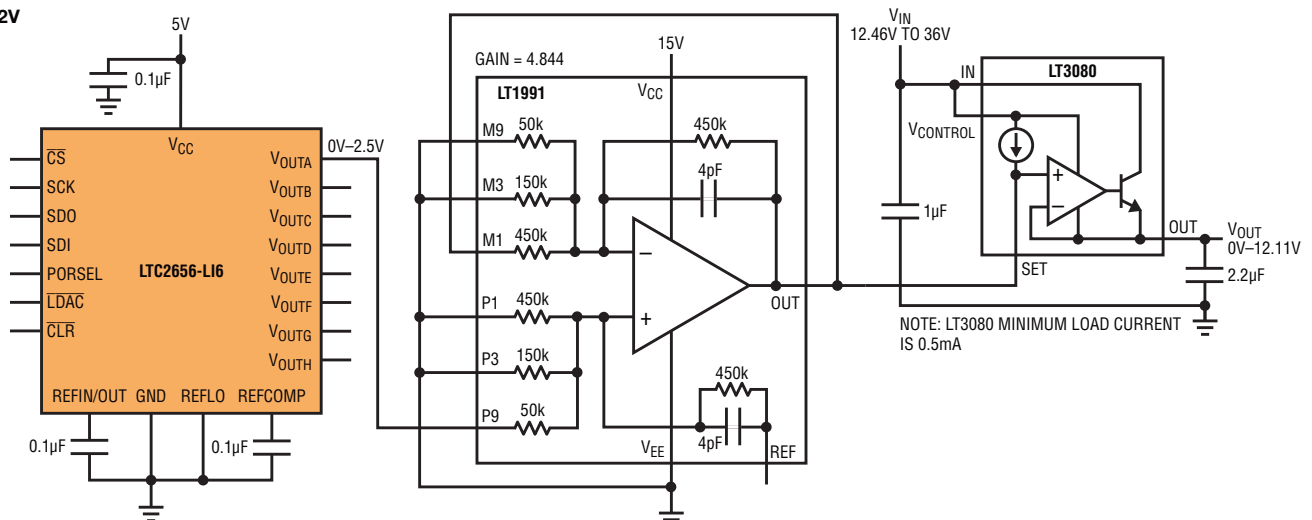
#### ADDING THE LT1991 TO ADJUST OUTPUT RANGE

The LTC2656-H combined with an LT3080 provides a nice digitally controlled 1.1A power supply with an output range from 0V to 4.096V. However, should the

user need a wider output range than what that particular circuit offers, there is an LTC part that provides an easy solution.

The LT1991 is a micropower precision gain selectable amplifier. It combines a precision op amp with eight precision matched resistors in a small package. Using the

Figure 4. Expanding the power supply output range to 0V-12V



LT1991 eliminates the need for any expensive external precision gain setting resistors. Gain can be set by simply changing how the input pins are connected, which in turn changes how the internal precision resistors set the gain of the op amp.

The limiting factor in output range of the LTC2656-LT3080 circuit is the output range of the LTC2656. The LT3080 is fully capable of going all the way up to 36V, however the DAC output at the SET pin is limited to 4.096V which in turn limits the output of the regulator. This hurdle is easily overcome by adding an LT1991 between the output of the LTC2656 and the SET pin of the LT3080. The LT1991 expands the output range of the DAC, which in turn sets the output range of the LT3080.

The LT1991 standard grade has 0.08% gain accuracy and 100 $\mu$ V offset, so there should be no degradation in performance of the DAC. With a maximum gain of 13 and a supply range of 40V, the LT1991 can stretch the DAC output range to match that of the LT3080. Typical output ranges such as 0V–10V (Figure 3) and 0V–12V (Figure 4) are easily achieved.

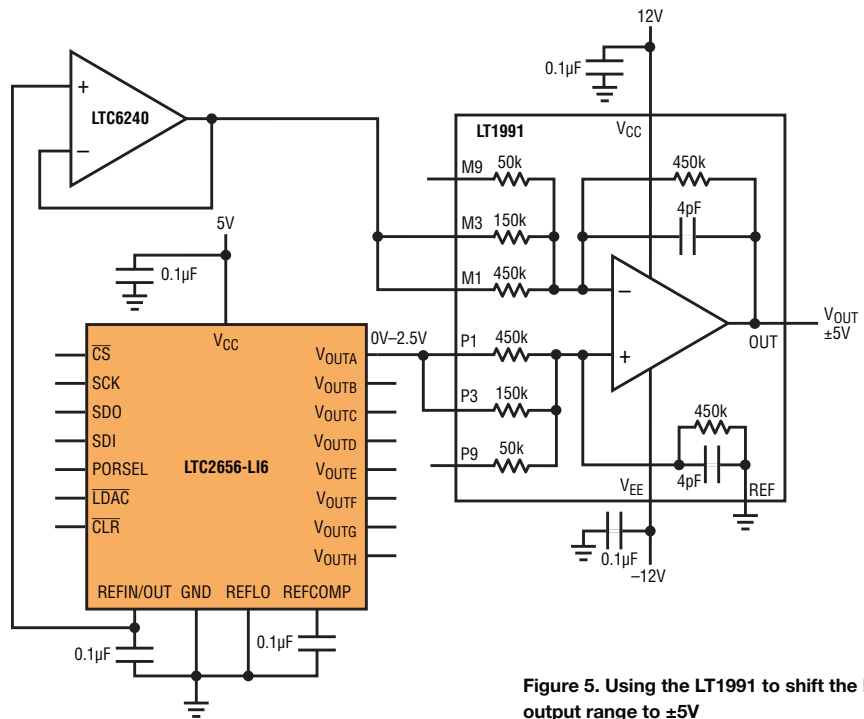


Figure 5. Using the LT1991 to shift the LTC2656 output range to  $\pm 5$ V

### USING THE LT1991 TO GO BIPOLAR

While the LTC2656 does come in two flavors, neither one is capable of a bipolar output. This again is a situation where the LT1991 proves its mettle. Using a combination of gain and offset, the LT1991 can be combined with the LTC2656 to form circuits that provide a  $\pm 5$ V output

(Figure 5), a  $\pm 10$ V output (Figure 6) and a variety of other bipolar voltages.

As stated before, the LT1991 has the advantage of not requiring expensive external precision gain set resistors. While some users might balk at using a multichip solution in order to achieve a

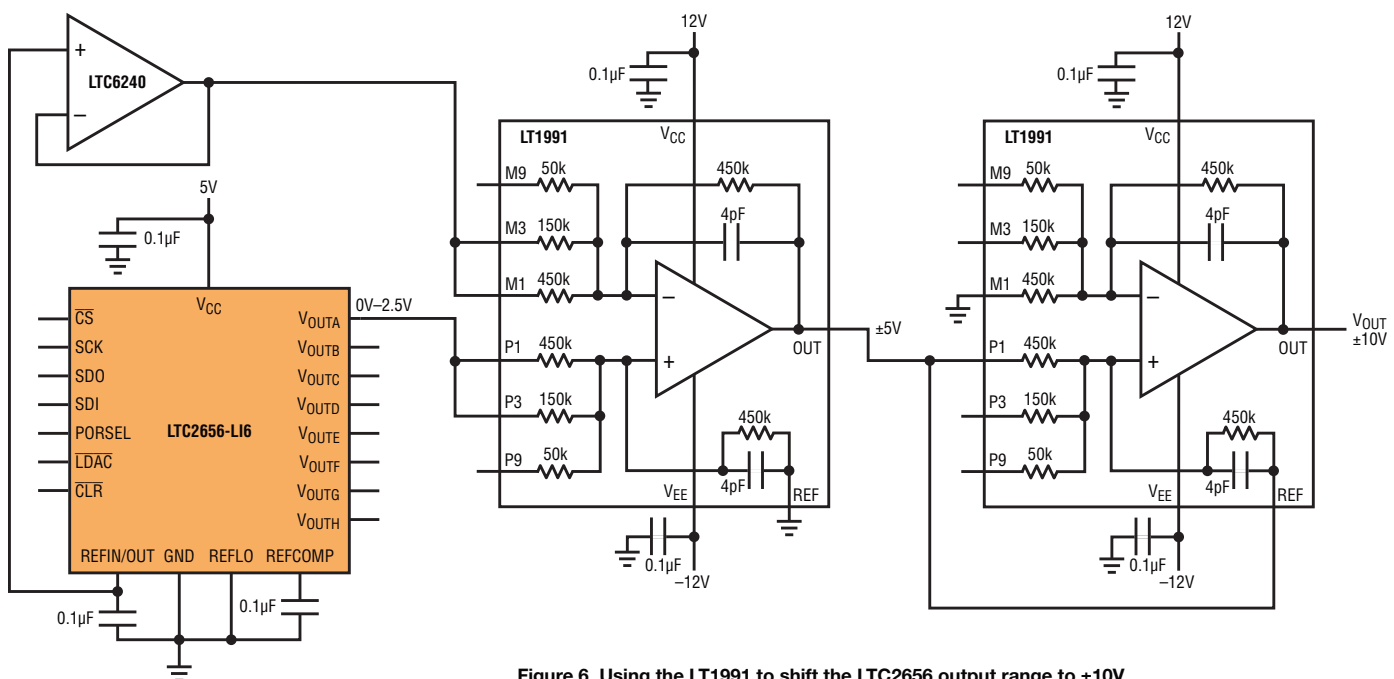


Figure 6. Using the LT1991 to shift the LTC2656 output range to  $\pm 10$ V

space equation while likely producing significant performance improvements.

**GOING ALL THE WAY TO GROUND**

The LTC2656 has unmatched offset performance, and its output can swing within 3mV of ground. For applications requiring the outputs to go completely to the lower supply rail, some additional circuitry, in the form of a Schottky diode and pull-down resistor, must be added (Figure 7).

The pull-down resistor forces the amplifier's pull-up stage to turn on. With the pull-up stage turned on, the output loop is correctly closed, putting the amplifier back into regulation. The Schottky diode prevents the output from being driven far below ground during power-up or when the DAC is placed into shutdown.

**LINKING MULTIPLE LTC2656s TO THE SAME REFERENCE**

When a design calls for more than the eight channels available in a single LTC2656, the SPI interface of the DAC allows for easy expansion.

When the application demands high precision matching between all analog

outputs, it is possible to drive all of the LTC2656 from a single internal reference. This is accomplished by tying the REFCOMP pin low on all but one of the DACs while also issuing the internal reference shutdown command through the digital interface. The one DAC with REFCOMP not tied to GND becomes the master reference, the REFIN/REFOUT pin of this DAC feeds into the REFIN/REFOUT pin on all the other DACs. All of the DACs on the board are thus driven from a single internal reference, avoiding variances in the respective reference outputs.

It is important to have the correct bypass capacitors in place at each of the reference inputs (Figure 8). The master reference should be treated similarly to a discrete reference during board layout and design.

**CONCLUSION**

The LTC2656 offers superior accuracy, precision and DAC density without the need for an external reference, thus reducing overall part count and footprint. It can be easily inserted into a wide variety of applications to solve otherwise intractable problems. ■

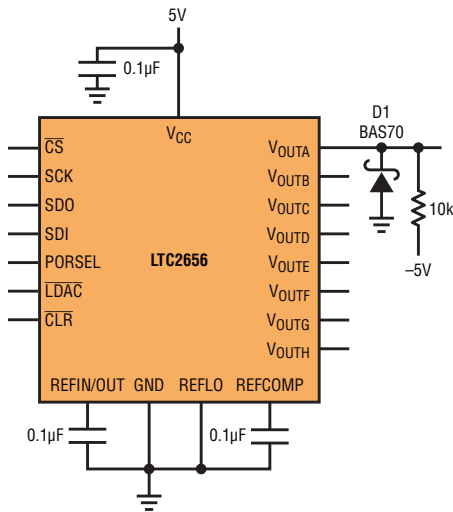
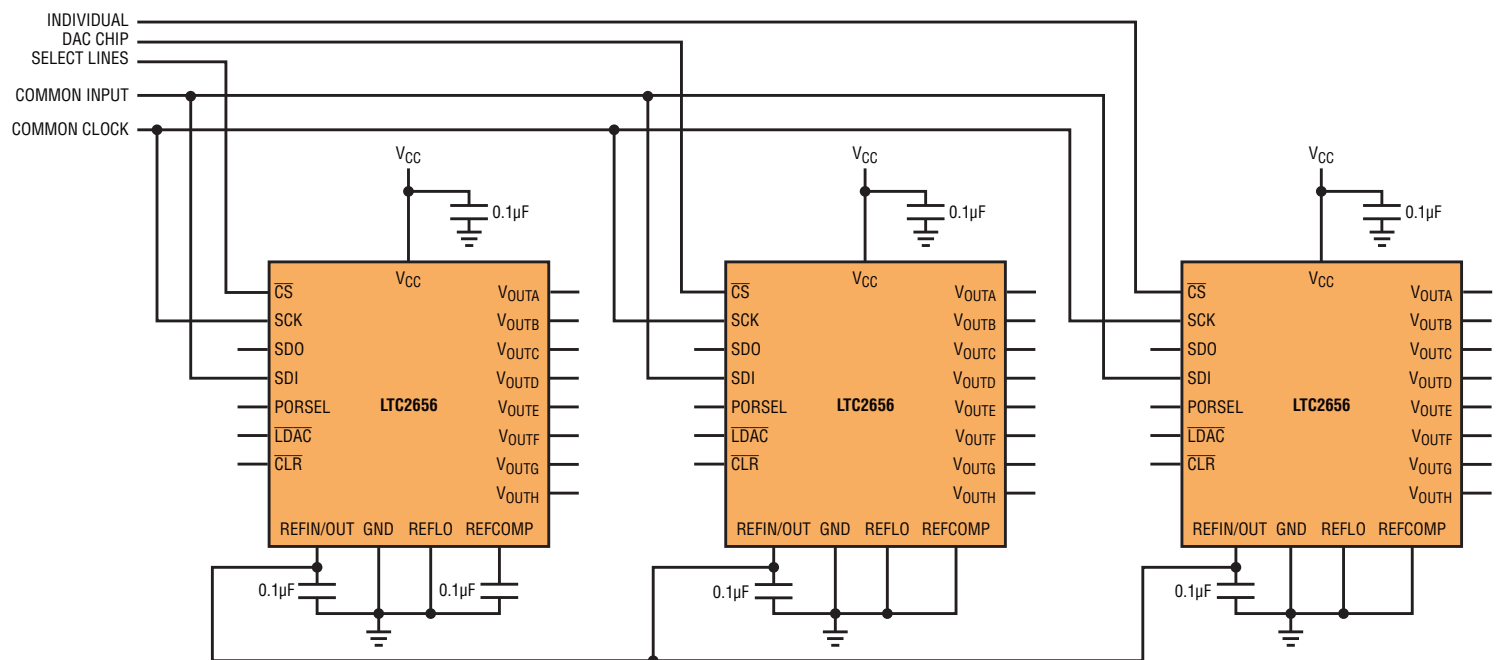


Figure 7. Achieving true rail-to-rail performance with the LTC2656

bipolar output, it is worth pointing out that the LTC2656 already saves space by eliminating the need for an external reference. Also, many bipolar DACs require an external op amp to convert a current output to a voltage anyway, so in the end, the LT1991 adds little to the board

Figure 8. Driving multiple LTC2656s with a single internal reference



# 6mm × 6mm DC/DC Controller for High Current DCR Sensing Applications

Eric Gu, Theo Phillips, Mike Shriver and Kerry Holliday

The LTC3855 is a versatile 2-phase synchronous buck controller IC with on-chip drivers, remote output voltage sensing and inductor temperature sensing. These features are ideal for high current applications where cycle-by-cycle current is measured across the inductor (DCR sensing). Either channel is suitable for inputs up to 38V and outputs up to 12.5V, further increasing the controller's versatility. The LTC3855 is based on the popular LTC3850, described in the October 2007 issue of *Linear Technology*.

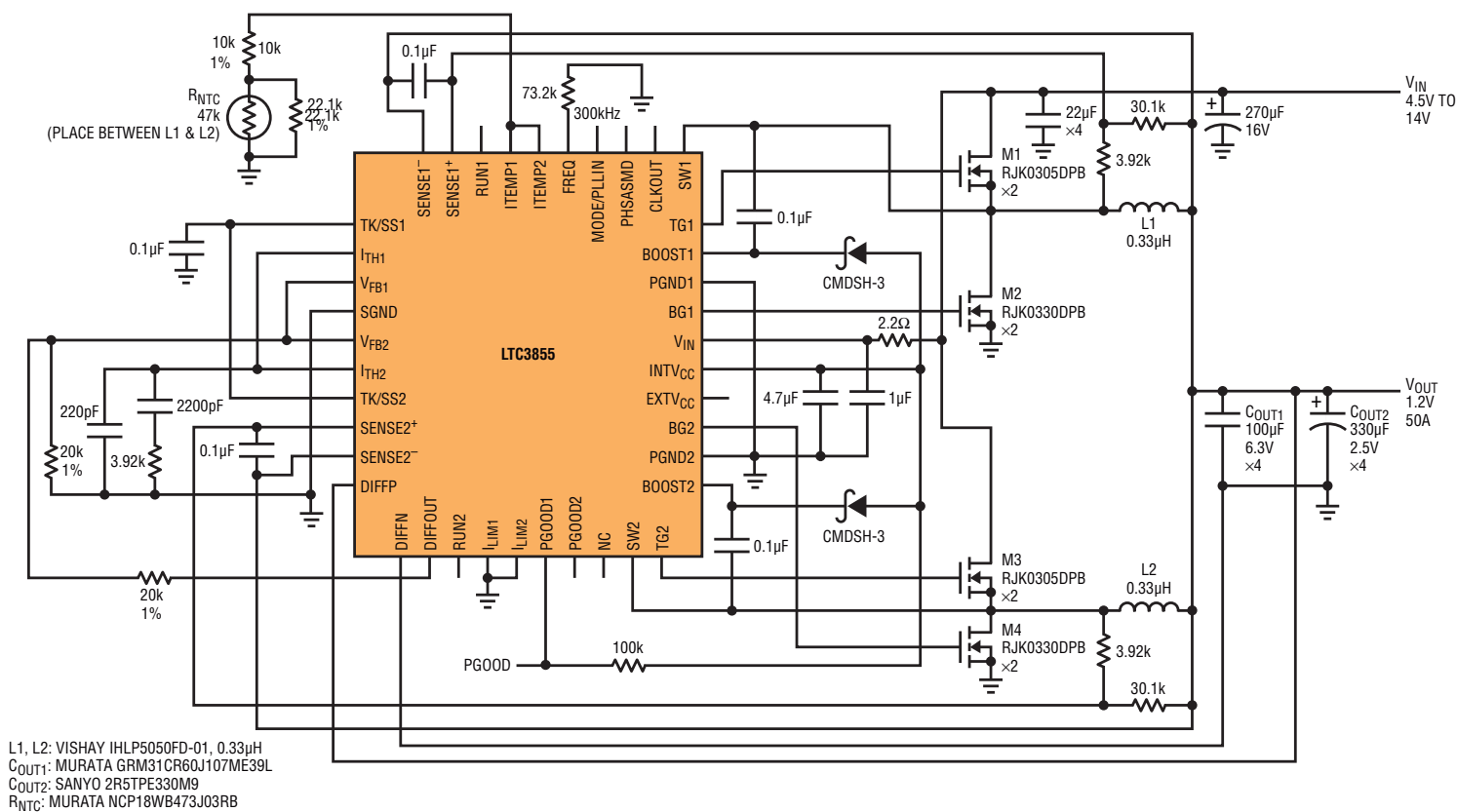
## MONITORING THE TEMPERATURE

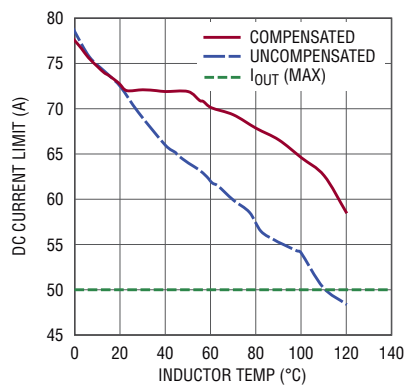
When current is sensed at the inductor, either a sense resistor is placed in series with the inductor, or an R-C network across the inductor is used to infer the current information across the inductor's DC resistance (DCR sensing). This

“lossless” method is less accurate than using a sense resistor, in large part because as the inductor heats up, its resistance increases with a temperature coefficient of resistivity (TCR) of 3930ppm/°C. Therefore as the temperature rises, the current limit decreases. When DCR sensing

is used, the current limit for the LTC3855 is determined by the peak sense voltage as measured across the inductor's DCR. The LTC3855 includes a temperature sensing scheme designed to compensate for the TCR of copper by effectively raising the peak sense voltage at high temperature.

Figure 1. A 1.2V, 50A, 2-phase converter. The two channels operate 180° out-of-phase to minimize output ripple and component sizes.





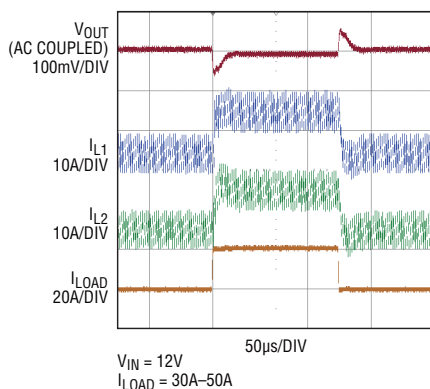
**Figure 2.** The converter of Figure 1 can deliver the current whether hot or cold, with its calculated worst-case current limit remaining above the target 50A, even well above room temperature.

## DIFFERENTIAL SENSING

At high load current, an offset can develop between the power ground, where  $V_{OUT}$  is sensed, and the IC's local ground. To overcome this load regulation error, the LTC3855 includes a unity gain differential amplifier for remote output voltage sensing. Inputs DIFFP and DIFFN are tied to the point of load, and the difference between them is expressed with respect to local ground from the DIFFOUT pin. Measurement error is limited to the input offset voltage of the differential amplifier, which is no more than 2mV.

## SINGLE OUTPUT CONVERTER WITH REMOTE OUTPUT VOLTAGE SENSING AND INDUCTOR DCR COMPENSATION

Figure 1 shows a high current DCR application with temperature sensing. The nominal peak current limit is determined by the sense voltage (30mV, set by grounding the ILIM pins) across the DC resistance of the inductor (typically 0.83mΩ), or 36A per phase. This sense voltage can be raised by biasing the ITEMP pins below 500mV. Since each ITEMP pin sources 10μA, peak sense voltage can be increased by inserting a resistance of less than 25k from ITEMP to ground. By using an inexpensive NTC thermistor placed near the inductors (with series and parallel



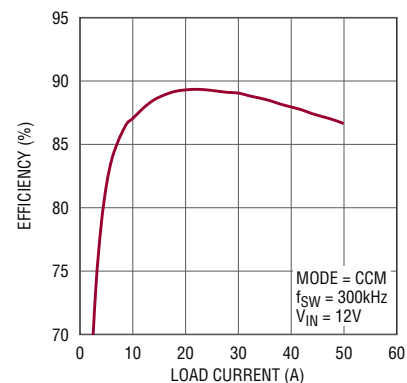
**Figure 3.**  $V_{OUT}$  is stable in the face of a 30A to 50A load step for the converter of Figure 1, and the inductor current sharing is fast and precise.

resistance for linearization), the current limit can be maintained above the nominal operating current, even at elevated temperatures (Figure 2).

The circuit also maintains precise regulation by differentially sensing the output voltage. The measurement is not contaminated by the difference between power ground and local ground. As a result, output voltage typically changes less than 0.2% from no load to full load.

## MULTIPHASE OPERATION

The LTC3855 can be configured for dual outputs, or for one output with both power stages tied together, as shown in Figure 1. In the single output configuration, both channels' compensation (ITH), feedback ( $V_{FB}$ ), enable (RUN) and track/soft-start (TRK/SS) pins are tied together, and both PGOOD1 and PGOOD2 will indicate the power good status of the output voltage. By doubling the effective switching frequency, the single output configuration minimizes the required input and output capacitance and voltage ripple, and allows for fast transient response (Figure 3). The LTC3855 provides inherently fast cycle-by-cycle current sharing due to its peak current mode architecture plus tight DC current sharing.



**Figure 4.** Efficiency for the converter of Figure 1.

## OTHER IMPORTANT FEATURES

A precise 10μA flows out of the FREQ pin, allowing the user to set the switching frequency with a single resistor to ground. The frequency can be set anywhere from 250kHz to 770kHz. If an external frequency source is available, a phase-locked loop enables the LTC3855 to sync with frequencies in the same range. A minimum on-time of 100ns allows low duty cycle operation even at high frequencies.

If the external sync signal is momentarily interrupted, the LTC3855 reverts to the frequency set by the external resistor. Its internal phase-locked loop filter is prebiased to this frequency. An internal switch automatically changes over to the sync signal when a clock train is detected. Since the PLL filter barely has to charge or discharge during this transition, synchronization is achieved in a minimum number of cycles, without large swings in switching frequency or output voltage.

The LTC3855 is also useful for designs using three or more phases. Its CLKOUT pin can drive the MODE/PLLIN pins of additional regulators. The PHASMD pin tailors the phase delays to interleave all the switch waveforms.

*(continued on page 35)*

# Maximize Cycle Life of Rechargeable Battery Packs with Multicell Monitor IC

Jon Munson

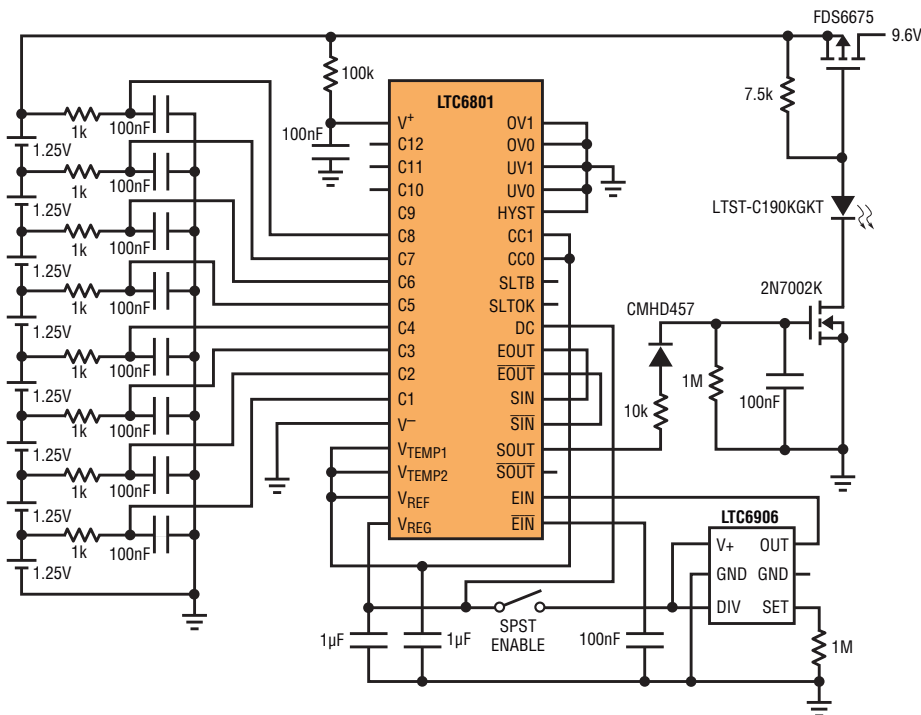
Rechargeable battery packs prematurely deteriorate in performance if any cells are allowed to overdischarge. As a pack becomes fully discharged, the  $I_{LOAD} \cdot R_{INTERNAL}$  voltage drop of the weakest cell(s) can overtake the internal  $V_{CELL}$  chemical potential and the cell terminal voltage becomes negative with respect to the normal voltage. In such a condition, irreversible chemical processes begin altering the internal material characteristics that originally provided the charge storage capability of the cell, so subsequent charge cycles of the cell do not retain the original energy content. Furthermore, once a cell is impaired, it is more likely to suffer reversals in subsequent usage, exacerbating the problem and rapidly shortening the useful cycle life of the pack.

With nickel-based chemistries, an over-discharge of a set of series-connected cells does not necessarily lead to a safety hazard, but it is not uncommon for one or more cells to suffer a reversal well before the user is aware of any significant degradation in performance. By then, it is too

late to rehabilitate the pack. In the case of the more energetic lithium-based cell chemistries, reversals must be prevented as a safety measure against overheating or fire. Monitoring the individual cell voltages is therefore essential to ensure a long pack life (and safety with lithium cells).

Enter the LTC6801, developed to provide integrated solutions for these specific problems. The LTC6801 can detect individual cell overvoltage (OV) and undervoltage (UV) conditions of up to twelve series connected cells, with cascadable interconnections to handle extended chains of devices, all independent of any microprocessor support.

Figure 1. Simple load-disconnect circuit to prevent excessive discharge of a nickel-cell pack.



## FEATURES OF THE LTC6801

The operating modes and programmable threshold levels are set by pin-strap connections. Nine UV settings (from 0.77V to 2.88V) and nine OV settings (from 3.7V to 4.5V) are available. The number of monitored cells can be set from 4 to 12 and the sampling rate can be set to one of three different speeds to optimize the power consumption versus detection time. Three different hysteresis settings are also available to tailor behavior of the alarm recovery.

To support extended configurations of series-connected cells, fault signaling is transmitted by passing galvanically isolated differential clock signals in both directions in a chain of “stacked” devices, providing excellent immunity to load

Cell reversal is a primary damage mechanism in traditional nickel-based multicell packs and can occur well before other noticeable charge-exhaustion symptoms appear.

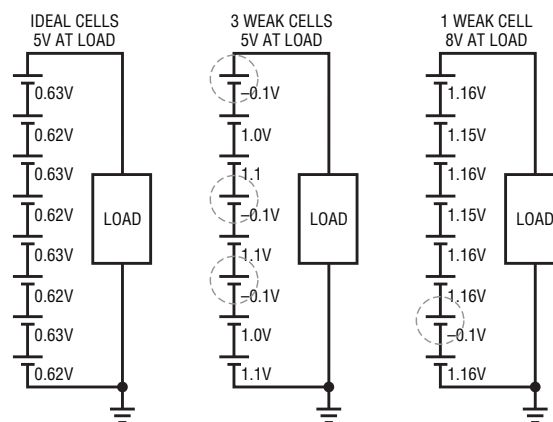
noise impressed on the battery pack. Any device in the chain detecting a fault stops its output clock signal, thus any fault indication in the entire chain propagates to the “bottom” device in the stack. The clock signal originates at the bottom of the stack by a dedicated IC, such as the LTC6906, or a host microprocessor if one is involved, and loops completely through the chain when conditions are normal.

In many applications, the LTC6801 is used as a redundant monitor to a more sophisticated acquisition system such as the LTC6802 (for example, in hybrid automobiles), but it is also ideal as a standalone solution for lower-cost products like portable tools and backup power sources. Since the LTC6801 takes its operating power directly from the batteries that it monitors, the range of usable cells per device varies by chemistry in order to provide the needed voltage to run the part—from about 10V up to over 50V. This range supports groupings of 4–12 Li-ion cells or 8–12 nickel-based cells. Figure 1 shows how simply an 8-cell nickel pack can be monitored and protected from the abuse of overdischarge. Note that only an under-voltage alarm is relevant with the nickel chemistries, though a pack continuity fault would still be detected during charging by the presence of an OV condition.

#### AVOIDING CELL REVERSALS

Cell reversal is a primary damage mechanism in traditional nickel-based multicell packs and can actually occur well before other noticeable charge-exhaustion symptoms set in.

**Figure 2. Pack discharge conditions that promote cell reversals may not be apparent from load potential.**



Consider the following scenario. An 8-cell nickel-cadmium (NiCd) pack is powering a hand tool such as a drill. The typical user runs the drill until it slows to perhaps 50% of its original speed, which means that the nominal 9.6V pack is loading down to about 5V. Assuming the cells are perfectly matched as in the left diagram of Figure 2, this means that each cell has run down to about 0.6V, which is acceptable for the cells. However, if there is a mismatch in the cells such that perhaps five of the cells are still above 1.0V, then the other three would be below zero volts and suffer a reverse stress as shown in the middle diagram of Figure 2.

Even assuming that there is only one weak cell in the pack (a realistic scenario) as in the right diagram in Figure 2, the first cell reversal might well occur while the stack voltage is still 8V or more, with just a subtle reduction in perceived pack strength. Because of the inevitable mismatching that exists in practice, users unknowingly reverse cells on a regular basis, reducing

the capacity and longevity of their battery packs, so a circuit that makes an early detection of individual cell exhaustion offers significant added value to the user.

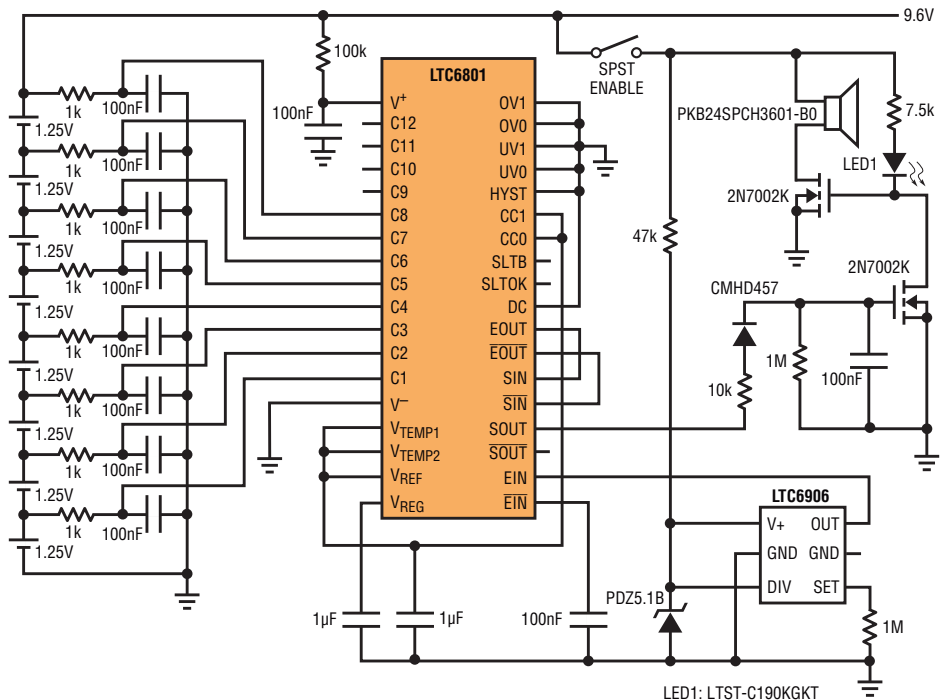
#### USING THE LTC6801 SOLUTION

The lowest available UV setting of the LTC6801 (0.77V) is ideal for detecting depletion of a nickel-cell pack. Figure 1 shows a MOSFET switch used as a load disconnect, controlled by the output state of the LTC6801. Whenever a cell becomes exhausted and its potential falls below the threshold, the load is removed so that cell reversal and its degradation effects are avoided. It also allows the maximum safe extraction of energy from the pack since there are no assumptions made as to the relative matching of the cells as might be the case with an overly conservative single pack-potential threshold function.

A 10kHz clock is generated by the LTC6906 silicon oscillator and the LTC6801 output status signal is detected and used to control the load disconnect action. Since

The LTC6801 simultaneously monitors up to 12 individual cells in a multicell battery pack, making it possible to maximize the pack's capacity and longevity. It can also be cascaded to support larger battery stacks.

**Figure 3. Alternative circuit provides an audible warning of the need to recharge the pack without interrupting service to the load.**



this example does not involve stacking of devices, the cascable clock signals are simply looped-back rather than passed to another LTC6801. An LED provides a visual indication that power is available to the load. Once the switch opens, the voltage of the weak cell tends to recover somewhat and the LTC6801 reactivates the load switch (no hysteresis with 0.77V under-voltage setting). The cycling rate of this digital load-limiting action depends on the configuration of the DC pin; in the fastest response mode ( $DC = V_{REG}$ ), the duty cycle of the delivered load power drops and tapers off, with pulsing becoming noticeable and slower as the weakest cell safely reaches a complete discharge.

In some applications it is not acceptable to spontaneously interrupt the load when the weakest cell is nearing full discharge as depicted in Figure 1. For those situations, the circuit of Figure 3 might be a good alternative. This circuit does not force a load intervention, but simply provides an audible alarm indication that the battery is near depletion. Here the LED provides an indication that the alarm is active and that no cells are exhausted.

An LTC6801 idle mode is invoked whenever the source clock is absent, and power consumption then drops to a minuscule 30µA, far less than the typical self-discharge of the pack. In both figures, the circuits show a switch that disables the oscillator (and other

peripheral circuitry) in order to place the circuit into idle mode when not being used so that battery drain is minimized.

### CONCLUSION

The LTC6801 simultaneously monitors up to 12 individual cells in a multicell battery pack, making it possible to maximize the pack's capacity and longevity. It can also be cascaded to support larger battery stacks. The device has a high level of integration, configurability and well thought out features, including an idle mode to minimize drain on the pack during periods of inactivity. This makes the LTC6801 a compact solution for improving the performance and reliability of battery powered products. ■



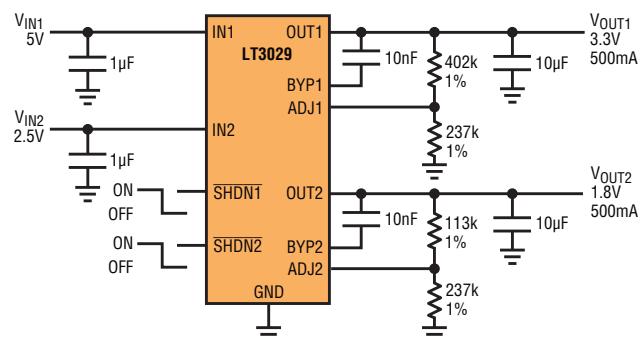
# Dual 500mA $\mu$ Power LDO Features Independent 1.8V–20V Inputs and Easy Sequencing in a 4mm $\times$ 3mm DFN

Molly Zhu

The LT3029 integrates two independent 500mA monolithic LDOs in a tiny 16-lead MSOP or 4mm  $\times$  3mm  $\times$  0.75mm DFN package. Both regulators have a wide 1.8V to 20V input voltage range with a 300mV dropout voltage at full load. The output voltage is adjustable down to the 1.215V reference voltage. With an external bypass capacitor, the output voltage noise is less than  $20\mu\text{V}_{\text{RMS}}$ . A complete power supply requires only a minimum  $3.3\mu\text{F}$  ceramic output capacitor for each channel to be stable.

Quiescent current is  $55\mu\text{A}$  per channel, dropping below  $1\mu\text{A}$  in shutdown. Reverse-battery protection, reverse-current protection, current limit fold-back and thermal shutdown are all

**Figure 1. Completely independent channels have separate input and SHDN pins.**



integrated into the package, making it ideal for battery-powered systems.

The LT3029 includes features that simplify the design of multivoltage systems. Its two independent regulators present separate input and shutdown pins. It is also compatible with the LTC2921, LTC2922 and LTC2923 power supply tracking controllers, allowing for easy multirail power supply tracking and sequencing design.

## TWO INDEPENDENT REGULATORS

The LT3029's inputs can be used independently or combined. Figure 1 shows an application generating two output voltages from two different input voltages, with independent shutdown control for each channel.

## DIFFERENT START-UP SLEW RATES

Start-up time is roughly proportional to the bypass capacitance, regardless of the input and output voltage. The output capacitance and the load characteristics also have no influence on the result. Figure 2 shows the regulator start-up time versus bypass capacitance.

The LT3029 is compatible with LTC292X series of power supply sequencing and tracking controllers. Its ADJ pin should be connected to LTC292X FB pin. By choosing the right resistors, it can track or sequence the power supply. Please refer to the LTC2923 data sheet for details.

*(continued on page 35)*

**Table 1. Comparison between dual channel LDOs**

	$V_{\text{IN}}$ RANGE (V)	$I_{\text{OUT}}$ (mA)	DROPOUT VOLTAGE @ $I_{\text{OUT}}$ (mV)	INDEPENDENT $V_{\text{IN}}$	$I_{\text{Q}}$ /CHANNEL ( $\mu\text{A}$ )	DFN PACKAGE SIZE
LT3023	1.8~20	100/100	300/300	N	20	3mm $\times$ 3mm
LT3024	1.8~20	100/500	300/300	N	30	4mm $\times$ 3mm
LT3027	1.8~20	100/100	300/320	Y	25	3mm $\times$ 3mm
LT3028	1.8~20	100/500	300/300	Y	30	5mm $\times$ 3mm
LT3029	1.8~20	500/500	300/300	Y	55	4mm $\times$ 3mm

# Product Briefs

## POE+ PD/SWITCHER SUPPORTS SECURITY CAMERA 24V<sub>AC</sub>/ 12V<sub>DC</sub> AUXILIARY POWER APPLICATION

The LTC4278 joins Linear Technology's family of Power-over-Ethernet-Plus (POE+) powered device (PD) controller and integrated switching regulators, ideally suited for the next generation security cameras and other POE+ PD applications. The LTC4278-based PD can receive power from a POE source or from 24V<sub>AC</sub>/12V<sub>DC</sub> auxiliary power supplies. This wide input voltage range distinguishes the LTC4278 from other PD/switchers on the market today.

PD applications often incorporate the flexibility and reliability of receiving power from either a POE or auxiliary power source. A POE based power source can operate as high as 57V while an auxiliary power source may come from a 12V wall adapter. Furthermore, the switching regulator may need to operate an additional three diode drops below the auxiliary input voltage when a PD application requires both 12V<sub>DC</sub> and 24V<sub>AC</sub> inputs. (The diodes are required to rectify the 24V<sub>AC</sub> and support POE/AUX diode ORing.)

With the demand for such a wide input range, the LTC4278-based PD is ideally suited to handle POE and low voltage auxiliary power inputs. The SHDN pin provides a simple implementation for POE or auxiliary power priority when both power sources are available and ready.

A POE+ PD requires a high power efficiency delivery, particularly when operating near the POE+ 25.5W limit. The LTC4278 serves this application with an

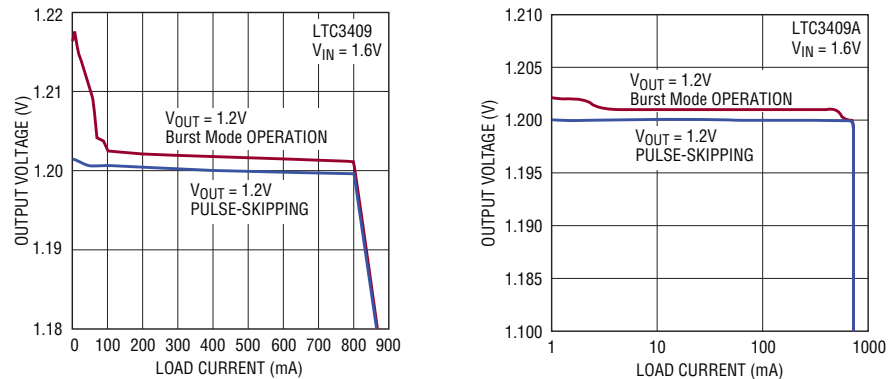


Figure 1. The LTC3409A (right graph) improves regulation over the LTC3409 (left)

onboard synchronous, current-mode, flyback controller that can implement Linear Technology's patented No-Opto feedback topology. This LTC4278-based topology is capable of delivering >92% isolated power supply efficiency, or >88% efficiency including diode bridges and Hot Swap™ FET. Furthermore, full IEEE 802.3 isolation is achieved without the need for an opto-isolator.

The LTC4278 is also fully equipped with POE detection, programmable classification load current and 2-event classification discovery. Inrush current limiting and a true soft-start function, both provide graceful ramp-up of line and all output voltages. Programmable timing, operating frequency, and the optional synchronized timing can be employed to optimize efficiency, component size, cost and EMI performance. Safety features include overvoltage, undervoltage and thermal shutdown, and the devices can be configured for short-circuit protection with auto restart.

## LOW V<sub>IN</sub> BUCK REGULATOR IMPROVES REGULATION IN BURST MODE OPERATION

The LTC3409A buck regulator features improved DC, line and load regulation in Burst Mode operation as compared to the LTC3409. These improvements are the result of reducing offsets in the regulator as well as increasing the regulator's DC gain and PSRR. Suggested output capacitance has also been increased to 44μF for optimal load regulation and stability. A stress relief coating has been applied to the die to minimize offset spreading resulting from encapsulation in the DFN plastic package.

Figure 1 shows the improvement in load regulation. The LTC3409A output voltage in Burst Mode operation consistently begins at a higher voltage at light loads dropping slightly as load increases, then dropping off at heavy loads. Due to process variations, the LTC3409's output voltage in Burst Mode operation can either start higher or lower at light loads compared to the output voltage when in continuous conduction mode at heavy loads.

### ULTRALOW VOLTAGE STEP-UP CONVERTER AND POWER MANAGER FOR ENERGY HARVESTING

The LTC3108 is a highly integrated DC/DC converter ideal for harvesting and managing surplus energy from extremely low input voltage sources such as TEG (thermoelectric generators), thermopiles and small solar cells. The step-up topology operates from input voltages as low as 20mV. Using a small step-up transformer, the LTC3108 provides a complete power management solution for wireless sensing and data acquisition.

The 2.2V LDO powers an external micro-processor, while the main output is programmed to one of four fixed voltages to power a wireless transmitter or sensors. The power good indicator signals that the main output voltage is within regulation. A second output can be

*(LTC3855 continued from page 29)*

The MOSFET drivers and control circuits are powered by INTV<sub>CC</sub>, which by default is powered through an internal low dropout regulator from the main input supply, V<sub>IN</sub>. If lower power dissipation in the IC is desired, a 5V supply can be connected to EXTV<sub>CC</sub>. When a supply is detected on EXTV<sub>CC</sub>, the LTC3855 switches INTV<sub>CC</sub> over to EXTV<sub>CC</sub>, with a drop of just 50mV. The strong gate drivers with optimized dead time provide high efficiency. The full load efficiency is 86.7% and the peak efficiency is 89.4% (Figure 4).

The LTC3855 features a RUN and TRACK/SS pin for each channel. RUN enables the output and INTV<sub>CC</sub>, while TRACK/SS acts as a soft-start or allows the outputs to track an external reference. If a multiphase output is desired, all RUN and TRACK/SS pins are typically tied to one another.

Peak current limiting is used in this application, with the peak sense voltage set by the three-state ILIM pin. A high speed rail-to-rail differential current

enabled by the host. A storage capacitor provides power when the input voltage source is unavailable. Extremely low quiescent current and high efficiency design ensure the fastest possible charge times of the output reservoir capacitor.

### POWERFUL SYNCHRONOUS N-CHANNEL MOSFET DRIVER IN A 2MM × 3MM DFN

The LTC4449 is high speed synchronous MOSFET driver designed to maximize efficiency and extend the operating voltage range in a wide variety of DC/DC converter topologies, from buck to boost to buck-boost.

The LTC4449's rail-to-rail driver outputs operate over a range of 4V to 6.5V and can sink up to 4.5A and source up to 3.2A of current, allowing it to easily drive high gate capacitance and/or multiple MOSFETS in parallel for high

sense comparator looks across the current sense element (here the inductor's DC resistance, implied from the associated R-C network). If a short circuit occurs, current limit foldback reduces the peak current to protect the power components. Foldback is disabled during start-up, for predictable tracking.

### CONCLUSION

The LTC3855 is ideal for converters using inductor DCR sensing to provide high current outputs. Its temperature compensation and remote output voltage sensing ensure predictable behavior from light load to high current. From inputs up to 38V it can regulate two separate outputs from 0.6V to 12.5V, and can be configured for higher currents by tying its channels together, or by paralleling additional LTC3855 power stages. At low duty cycles, the short minimum on-time ensures constant frequency operation, and peak current limit remains constant even as duty cycle changes. The LTC3855 incorporates these features and more into 6mm × 6mm QFN or 38-lead TSSOP packages. ■

current applications. The high side driver can withstand voltages up to 38V.

Adaptive shoot-through protection circuitry is integrated to prevent MOSFET cross-conduction current. With 14ns propagation delays and 4ns to 8ns transition times driving 3nF loads, the LTC4449 minimizes power loss due to switching losses and dead time body diode conduction.

The LTC4449 features a three-state PWM input for power stage control and shutdown that is compatible with all controllers that employ a three-state output feature. The LTC4449 also has a separate supply input for the input logic to match the signal swing of the controller IC. Undervoltage lockout detectors monitor both the driver and logic supplies and disable operation if the voltage is too low. ■

*(LT3029 continued from page 35)*

### CONCLUSION

The LT3029 is a dual 500mA/500mA monolithic LDO with a wide input voltage range and low noise. The two channels are fully independent, allowing for flexible power management. It is ideal for battery-powered systems because of its low quiescent current, small package and integration of battery protection features. ■

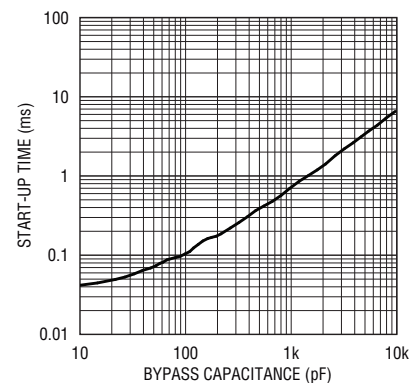
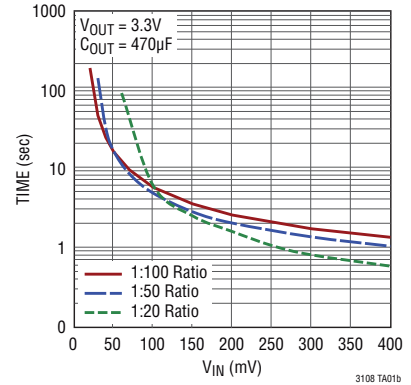
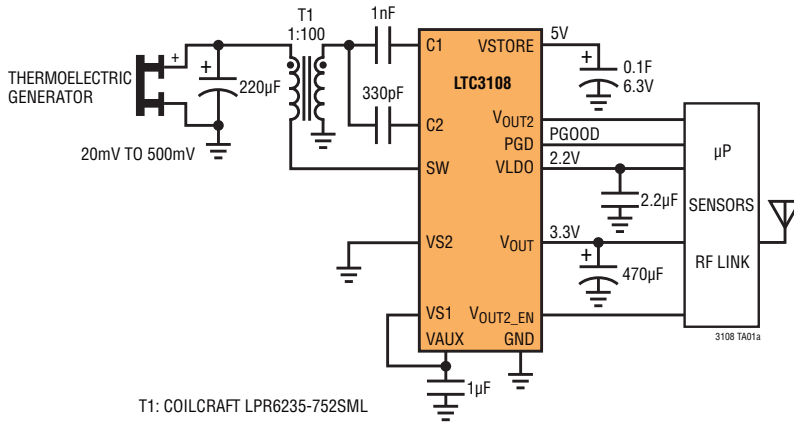


Figure 2. Start-up time vs bypass capacitor value

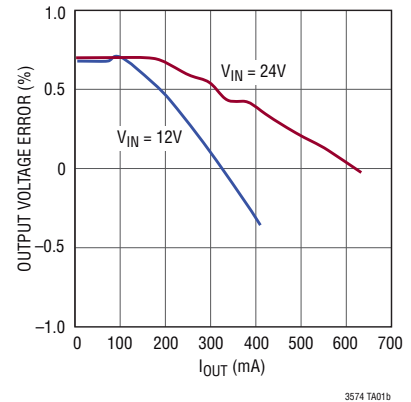
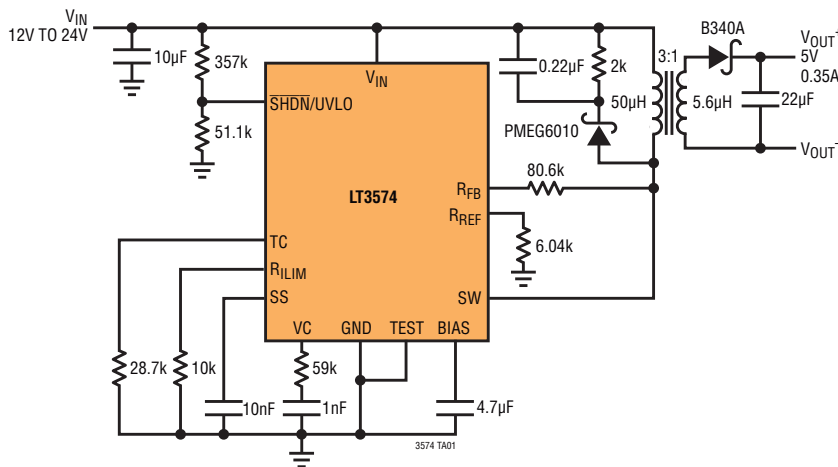
**WIRELESS REMOTE SENSOR APPLICATION POWERED FROM A PELTIER CELL**

The LTC3108 is a highly integrated DC/DC converter ideal for harvesting and managing surplus energy from extremely low input voltage sources such as TEGs (thermoelectric generators), thermopiles and small solar cells. Using a small step-up transformer, the LTC3108 can boost from input sources as low as 20mV to provide a complete power management solution for microprocessors, remote sensors, data acquisition circuitry and low power RF links. [www.linear.com/3108](http://www.linear.com/3108)



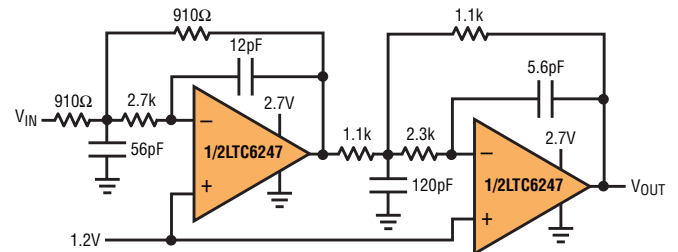
**5V ISOLATED FLYBACK CONVERTER**

The LT3574 is a monolithic switching regulator specifically designed for the isolated flyback topology. The part senses the isolated output voltage directly from the primary side flyback waveform—no third winding or opto-isolator is required for regulation. This circuit provides a simple, low component count isolated 5V supply from a 12V to 24V input. The output voltage is easily set by the resistor at RFB and RREF and the transformer turns ratio. [www.linear.com/3574](http://www.linear.com/3574)



**SINGLE 2.7V SUPPLY 4MHZ 4TH ORDER BUTTERWORTH FILTER**

The LTC6247 is a power efficient dual op amp that offers 180MHz gain-bandwidth product while consuming only 1mA of supply current per amplifier. This simple implementation of a Butterworth lowpass filter provides a low power, low noise 4MHz lowpass filter. Operating from a single 2.7V supply, the complete circuit dissipates less than 5mW of power. Both the input and output of the LTC6247 swing rail-to-rail, critical in maximizing dynamic range in low voltage systems. [www.linear.com/6247](http://www.linear.com/6247)



LT, LT, LTC, LTM, Linear Technology, the Linear logo, Burst Mode, and µModule are registered trademarks and Hot Swap and No Latency ΔΣ are trademarks of Linear Technology Corporation. All other trademarks are the property of their respective owners.

