LINEAR TECHNOLOGY

IN THIS ISSUE…

Breakthrough Buck-Boost Controller Provides up to 10A from a Wide 4V–36V Input Range

by Theo Phillips and Wilson Zhou

Introduction

Many DC/DC converter applications require an output voltage somewhere within a wide range of input voltages. An everyday example would be a well-regulated 12V output from an automotive battery input, which has a full charge voltage around 14V and a fluctuating cold crank voltage under 9V.

There are a number of traditional solutions to this problem, but all have drawbacks, including low efficiency, limited input voltage range or the use bulky coupled inductors. Some even produce output voltages of polarity opposite to that of the input voltage. A system designer must often decide between an inefficient topology or a scheme that uses both a boost regula-

tor and a buck regulator, which adds complexity with extra filter components and multiple control loops.

The LTC3780 offers a simpler solution with an approach that requires neither cumbersome magnetics nor additional control loops (see Figure 1). This 4-switch controller takes the form of a true synchronous buck or boost, depending on the input voltage. Transitions between modes depend on duty cycle (Figure 2) and are quick and automatic. The controller is versatile, providing three modes of operation, switching frequencies from 200kHz to 400kHz, and output currents from milliamps to tens of amps. The three operating modes permit the designer to choose between efficiency and low

4-SWITCH BUCK-BOOST TOPOLOGY YIELDS HIGH EFFICIENCY AT HIGH POWER

ONLY ONE INDUCTOR SIMPLIFIES LAYOUT AND SAVES SPACE

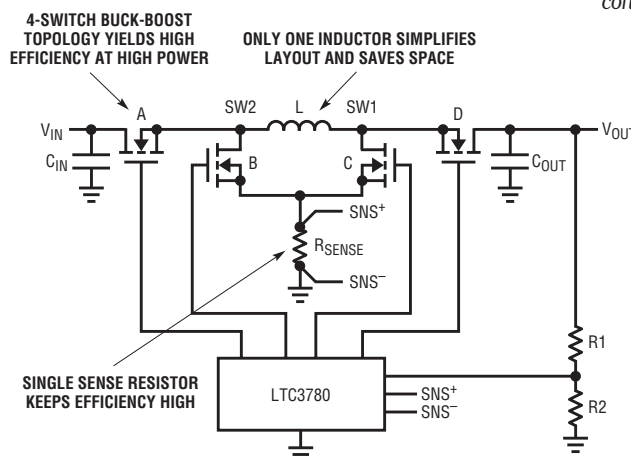**SINGLE SENSE RESISTOR KEEPS EFFICIENCY HIGH**

Figure 1. Simplified diagram of the LTC3780 topology, showing how the four power switches are connected to the inductor, V_{IN}, V_{OUT} and GND.

Issue Highlights

Many DC/DC converter applications require an output voltage somewhere within a wide range of input voltages. Traditional approaches to this problem can require cumbersome magnetics or additional control loops. The LTC®3780 offers a simpler, much more compact and high performance solution by taking the form of a true synchronous buck or boost, depending on the input voltage. Transitions between modes depend on duty cycle and are quick and automatic.

See our cover article for more about this breakthrough device.

Featured Devices

Below is a summary of the other devices featured in this issue.

Power Solutions

The LTC3417 is a **dual synchronous, step-down, current mode, DC/DC converter** designed for medium power applications. It operates from an input voltage between 2.25V and 5.5V and switches at up to 4MHz, making it possible to use low profile capacitors and inductors. (Page 7)

The LT3012 and LT3013 are **high voltage micropower regulators** designed for industrial and automotive environments. They offer an input voltage range of 4V to 80V and minimize power loss by running with quiescent currents of 55µA (LT3012) and 65µA (LT3013). Quiescent current is reduced to just 1µA in shutdown. (Page 11)

The LTC3456 is a **complete system power IC** that seamlessly manages power flow between an AC wall adapter, USB and 2-AA battery, while complying with USB power standards—all in a 4mm × 4mm QFN package. (Page 13)

The LTC4061 and LTC4062 are specifically designed to **charge single-cell lithium-ion batteries** from either awall adapter or available USB power. Both devices use constant current/constant voltage algorithms to deliver up to 1A of charge current. (Page 20)

The LTC3409 is a **monolithic synchronous step-down regulator** designed specifically to save space, improve battery life and simplify the design of 2-cell-alkaline, NiCd and NiMh powered applications. (Page 22)

The LTC2927 provides simple **tracking and sequencing solutions** in a tiny footprint, without the drawbacks of series MOSFETs. (Page 24)

The LT3724 is a **single-switch DC/DC controller** that can be used in medium power step-down, step-up, inverting and SEPIC converter topologies. (Page 28)

High Performance ADCs

Many of today's data acquisition applications require low-power and/or remote sensing capabilities while occupying a minimum amount of board space. Linear Technology introduces a pin-compatible family of **12-bit and 16-bit A/D converters** that meet these requirements. (Page 31)

Micropower Op Amps

The LTC6078 and LTC6079 are dual and quad **micropower, precision op amps** that combine the low offset and drift of traditional bipolar amplifiers with the low bias current of CMOS amplifiers. They include a combination of features that allow precision performance previously available only through composite amplifiers, manual offset trimming, or calibration.(Page 9)

Precision Silicon Oscillator

The LTC6906 is a **monolithic silicon oscillator** with significant size, power, cost and environmental sensitivity advantages over other oscillators. It requires only a single external resistor to set the frequency over its full range of 10kHz to 1MHz. (Page 17)

Design Ideas and Cameos

The Design Ideas start on page 35, including a discusion of Ni-based battery chargers and a way to determine the real resistance of a battery. *LT*

Linear Technology in the News...

Linear Tops $1 Billion

On July 26, Linear Technology Corporation announced financial results for its fiscal year 2005, ending July 3, 2005. According to Lothar Maier, CEO, "Fiscal 2005 was a good year for us in what was generally described as a slow growth environment, and our rate of sales growth was greater than all of our major competitors, allowing us to achieve over $1 billion in revenues for the first time in the Company's history."

Products in the News

Leading Edge... The May 12 edition of *EDN* featured the LT5527 400MHz to 3.7GHz High Signal Level Downconverting Mixer in the "Leading Edge" section of the magazine. The "Leading Edge" column focuses on what's hot in the design community.

Mixer Times Two... The June issue of *Wireless Design & Development* featured the LT5527 in their "What's Hot" section. Electronic Products also featured the LT5527 in the June Highlights section.

Design Update... *Electronics Weekly* (UK) featured Linear Technology's LTC2950 push button on/off controller chip, which includes debounce, power supply enable and processor interface on the cover of the May 4 issue. The part enables the power supply converter and releases the processor once the supply is fully powered up. When powering off, the chip interrupts the system processor to alert it to perform housekeeping tasks. Once these tasks are over, the processor can command the LTC2950 to disable power immediately. *LT*

ripple at light loads. The frequency can be selected by applying the proper voltage to the PLLFLTR pin, or the controller can be synchronized to an external clock via an internal phase-lock loop. The current sensing resistor programs the current limit, freeing the designer to choose among a broad array of power MOSFETs. Efficiency in a typical application reaches 97%, and exceeds 90% over more than a decade of load current (Figure 3). The output remains stable despite transients in load current (Figure 4) and line voltage (Figure 5).

A 12V, 5A Converter Operating from Wide Input Voltage Range

Figure 6 shows a versatile LTC3780-based converter providing 12V at up to 5A with inputs from 5V to 32V; the core circuit fits in a cubic inch with a footprint of only 2.5in² as shown in Figure 7. This converter can operate with any of three light-load operating modes, set at the three-state FCB pin: continuous current mode, discontinu-

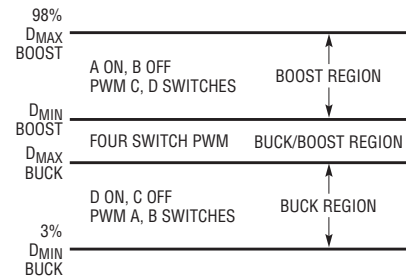| 98% D_{MAX} BOOST | A ON, B OFF PWM C, D SWITCHES | BOOST REGION |
D_{MIN} BOOST		
	FOUR SWITCH PWM	BUCK/BOOST REGION
D_{MAX} BUCK		
	D ON, C OFF PWM A, B SWITCHES	BUCK REGION
3% D_{MIN} BUCK		

Figure 2. The duty cycle determines the operating mode, whether in continuous mode (pictured) or in any of the power saving modes. The power switches are properly controlled so the transfer between modes is continuous. When V_{IN} approaches V_{OUT}, the buck-boost region is reached; the mode-transition time is typically 300ns.

ous current mode and Burst Mode® operation (which becomes skip cycle mode at higher input voltages). These modes allow a designer to optimize efficiency and noise suppression. Continuous operation provides very low output voltage ripple, since at least one of the switch nodes is always cycling at a constant, programmed frequency. With at least one switch always on, the lowest possible noise is achieved since the output L-C filter is not permitted to ring.

In continuous operation, the power switches' operating sequence depends on whether the input voltage is greater than, nearly the same as, or less than the desired output voltage. When the input is well above the output (buck mode), Switch D remains on and switch C shuts off. When each cycle begins, synchronous switch B turns on first and the inductor current is determined by comparing the voltage across R_{SENSE} to an internal reference. When the sense voltage drops below the reference, synchronous switch B turns off and switch A is turns on for the remainder of the cycle. Switches A and B turn on and off alternately, behaving like a typical synchronous buck regulator. The duty cycle of switch A increases until the maximum duty cycle of the converter in buck mode reaches 94%–96%.

Figure 8a shows conceptual waveforms in this buck region. When the input voltage comes close to the output voltage, maximum duty cycle is reached and the LTC3780 shifts to buck-boost mode. Figures 8b and 8c show the symmetrical, input voltage-
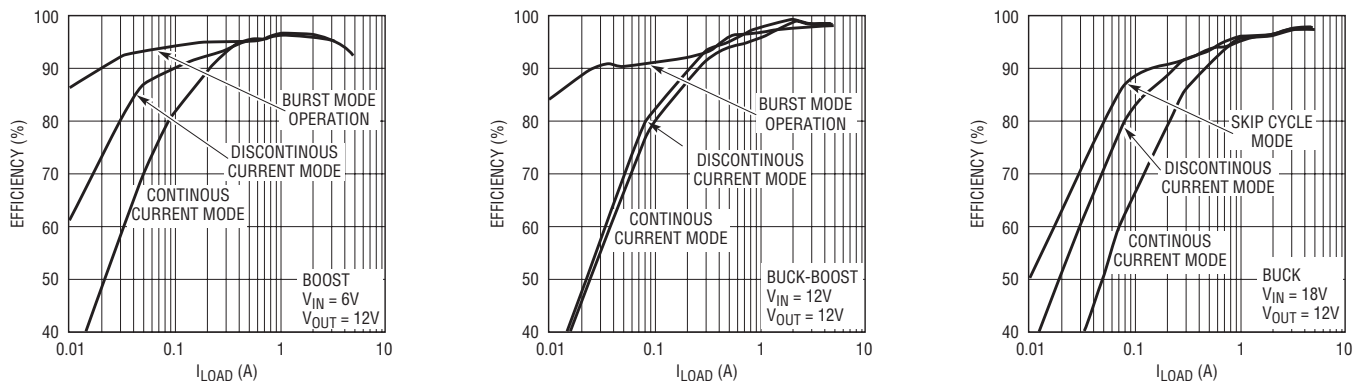
Figure 3. Efficiency is high throughout the range of load currents and operating modes.
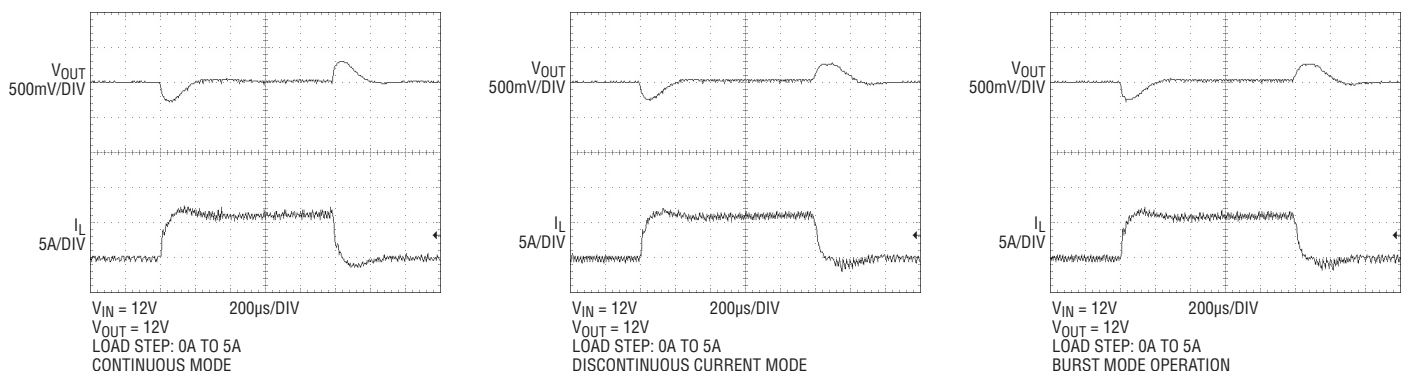
Figure 4. The LTC3780 provides excellent load transient response in any of its operating modes.
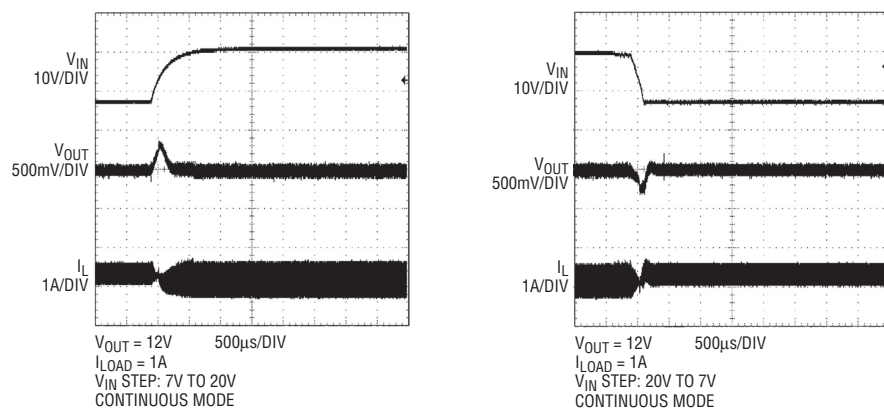
Figure 5. The LTC3780 responds quickly to changing input voltages.

dependent behavior of the switches in this region. If the cycle starts with switches B and D turned on, switches A and C turn on. Then, switch C turns off, switch A remains on, and switch D turns on for the remainder of the cycle; but if the controller starts with switches A and C turned on, switches B and D turn on. Then, switch B turns off, switch D remains on, and switch A turns on for the remainder of the cycle.

Figure 8d shows typical behavior when the input is well below the output (boost mode). Here, switch A is always on and synchronous switch B is always off. When each cycle begins, switch C turns on first and the inductor current is monitored via R_{SENSE}. When the voltage across R_{SENSE} rises
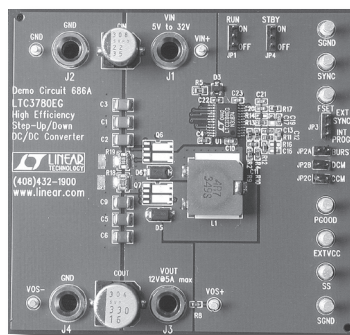
Figure 7. Typical LTC3780 layout. The four MOSFETs are on the reverse side, with space available on top for two dual MOSFETs.

above the reference voltage, switch C turns off and synchronous switch D turns on for the remainder of the cycle. Switches C and D turn on and off alternately, behaving like a typical synchronous boost regulator.

The duty cycle of switch C decreases until the minimum duty cycle of the converter in boost mode reaches 4%–6%.

When this minimum duty cycle is reached, the LTC3780 shifts into buck-boost mode.

Like continuous current mode, discontinuous current mode features constant frequency and extremely low ripple, and improves efficiency at light loads by turning off the relevant synchronous switch (B or D). In boost mode, switch D remains off if the load is light enough. In buck mode, switch B turns on every cycle, just long enough to produce a small negative inductor current; this sequence maintains constant frequency operation even at no load (Figure 9).

Burst Mode (in boost operation, Figure 10) and Skip Cycle mode (in buck operation, Figure 11) provide the highest possible light load efficiency. In Burst Mode operation, switches C and D operate in brief pulse trains

Figure 6. An LTC3780-based DC/DC converter delivering 12V/5A from a 5V–32V input.

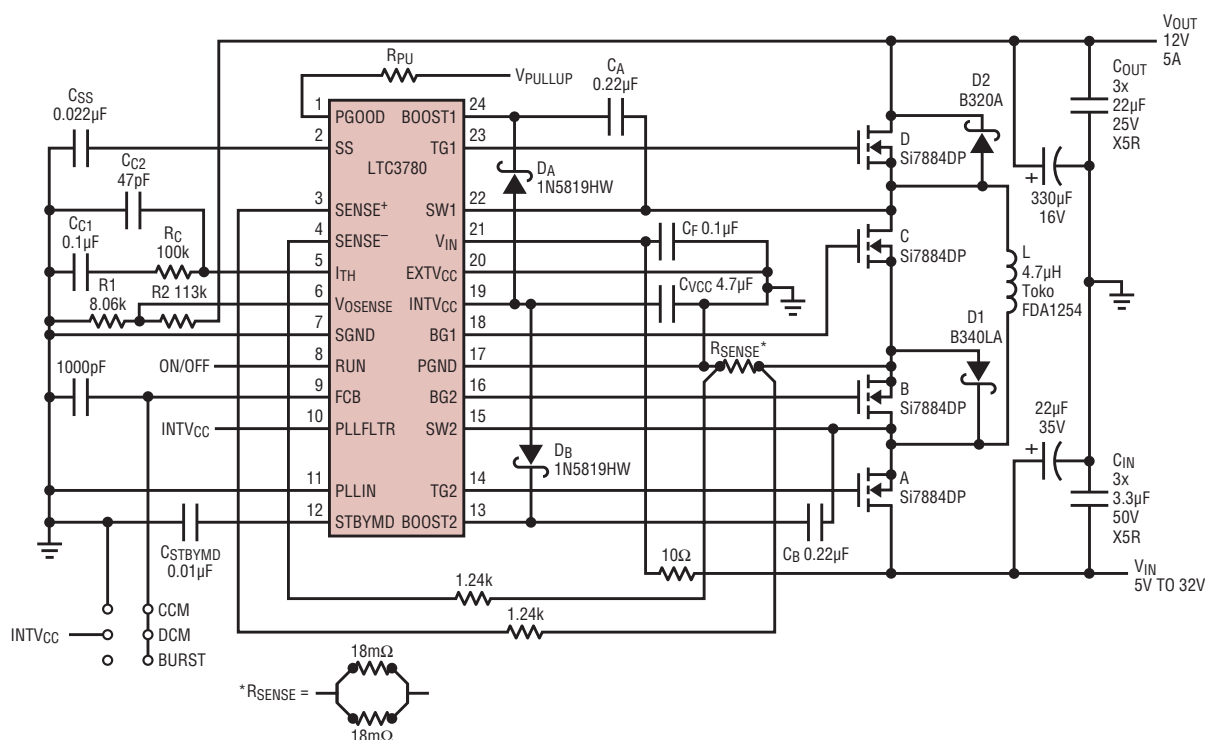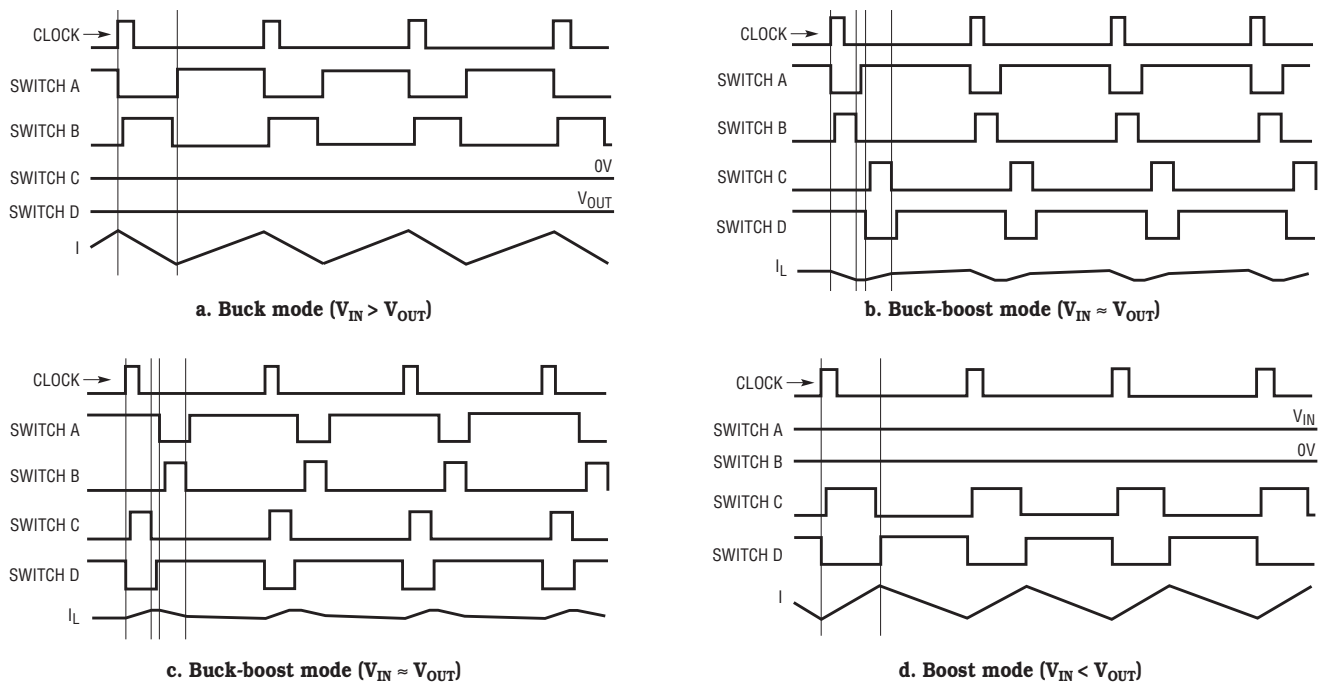**a. Buck mode ($V_{IN} > V_{OUT}$)**

b. Buck-boost mode ($V_{IN} \approx V_{OUT}$)

c. Buck-boost mode ($V_{IN} \approx V_{OUT}$)

d. Boost mode ($V_{IN} < V_{OUT}$)

Figure 8. Power switch gate drive control in continuous conduction mode, in various regions of operation.

while holding switch A on. Skip Cycle mode only turns on the synchronous buck switch B when the inductor current reaches a minimum positive level, which does not happen every cycle at very light loads. Since energy devoted to switching dominates the power loss picture at very light loads, both of these switching arrangements raise efficiency.

A single sense resistor placed between ground and the source terminals of both synchronous MOSFETs determines the current limit. It reliably governs the valley of the inductor current in buck mode and the maximum

inductor peak current in boost mode. The LTC3780 monitors the current via an internal comparator. This single sense resistor structure dissipates little power (compared with multiple resistor sensing schemes) and provides consistent current information for short circuit and over current protection.

Flexible Power

Although the LTC3780 is ideal for applications where the range of possible input voltages straddles the output voltage in everyday operation, it is also useful as a dedicated synchronous

buck or boost controller. Applications requiring a fixed output from a variety of input rails can benefit from the simplicity of a single drop-in design. At a minimum, the same layout can be repeated, with power switches and passive components scaled to the particular input voltage and output load requirements.

The LTC3780 is by itself an outstanding synchronous boost controller. Dedicated boost controllers typically have narrower input or output voltage ranges than the LTC3780, and nonsynchronous versions (the most common type) suffer from signifi-

DISCONTINUOUS CURRENT MODE
BUCK MODE
NO LOAD
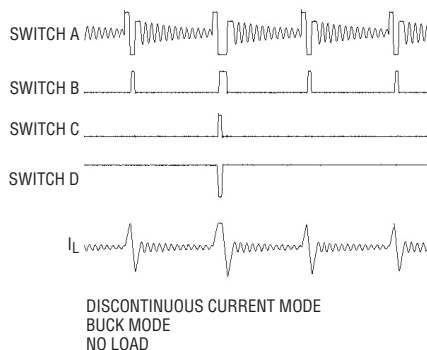
Figure 9. Switch operation in discontinuous current mode, buck mode, no load. Switch B turns on every cycle, until the inductor current goes slightly negative. The inductor current then free-wheels through the body diode of switch B (or a Schottky diode in parallel with it). Switches C and D occasionally trigger to refresh switch D's bootstrap capacitor.

BURST MODE
BOOST MODE
NO LOAD
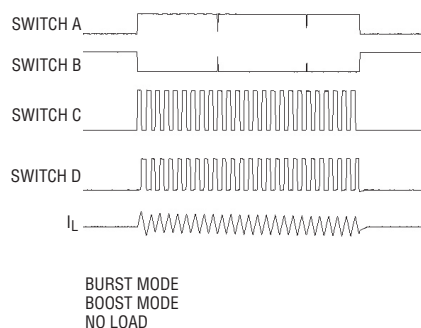
Figure 10. Switch operation in Burst Mode operation, boost mode, no load. Switches A and B are toggled to connect the true boost converter directly to the input rail, with occasional refresh pulses for switch A's bootstrap capacitor. During the sleep period between bursts, switches A, C, and D remain off.

SKIP CYCLE MODE
BUCK MODE
NO LOAD
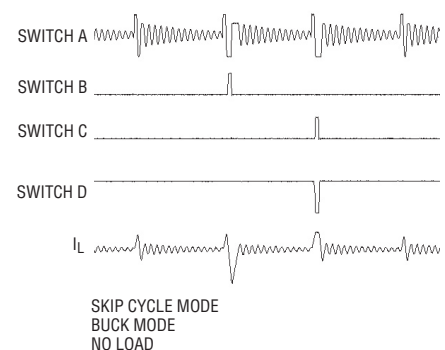
Figure 11. Switch operation in skip cycle mode, buck mode, no load. Note the similarity to discontinuous current mode, except switch B is not turned on every cycle. In this way, energy is saved by allowing the inductor to discharge through the body diode of switch B (or the Schottky diode across it, if there is one).
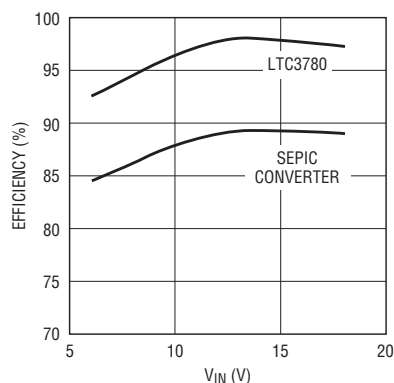
Figure 12. The LTC3780 12V/5A converter beats a SEPIC in efficiency across the board.

Figure 13. They may be similar in functionality, but not even close in size. The hulking inductor in the SEPIC on the left casts a big shadow on its counterpart in the LTC3780-based 12V/5A application on the right.

cant power loss in the free-wheeling Schottky diode. Compared to a typical non-synchronous boost converter, the circuit of Figure 6 can yield an increase of over 5% in efficiency at moderate loads.

Surpassing the SEPIC

Whatever the operating mode, the single inductor buck-boost structure has high power density and high efficiency. Compared wit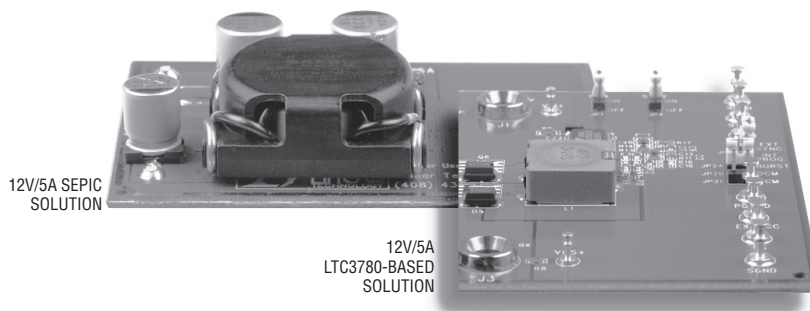h a coupled inductor SEPIC converter, its efficiency can be 8% higher. Figure 12 shows the efficiency comparison between a typical LTC3780 12V/5A application and a SEPIC converter, which is not

only less efficient but quite a bit larger. A SEPIC transformer would occupy twice the footprint of the inductor in
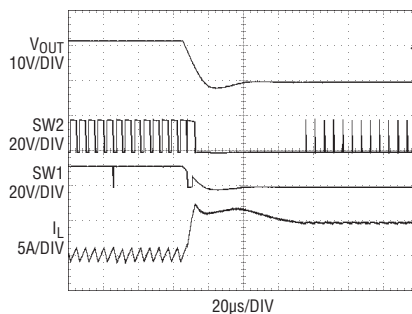
Figure 14. Current foldback handles short circuits without dragging down the input rail. V_{IN}, represented here by the peaks of SW2, remains solid.

our buck-boost example, and would stand twice as high (Figure 13).

Even the large off-the-shelf coupled inductor of Figure 13 would be insufficient for the current levels seen when boosting 5V to 12V at 5A—a safe minimum input voltage would be around 6V. To convert 32V to 12V, a SEPIC would require a power switch rated at 60V (the lowest prevailing drain-to-source voltage $> V_{IN} + V_{OUT}$), yet the output current would demand a low $R_{DS(ON)}$, requiring multiple SO-8 MOSFETs or a much larger TO-220. The coupling element would consist of large, expensive, high voltage ceramic capacitors, in addition to
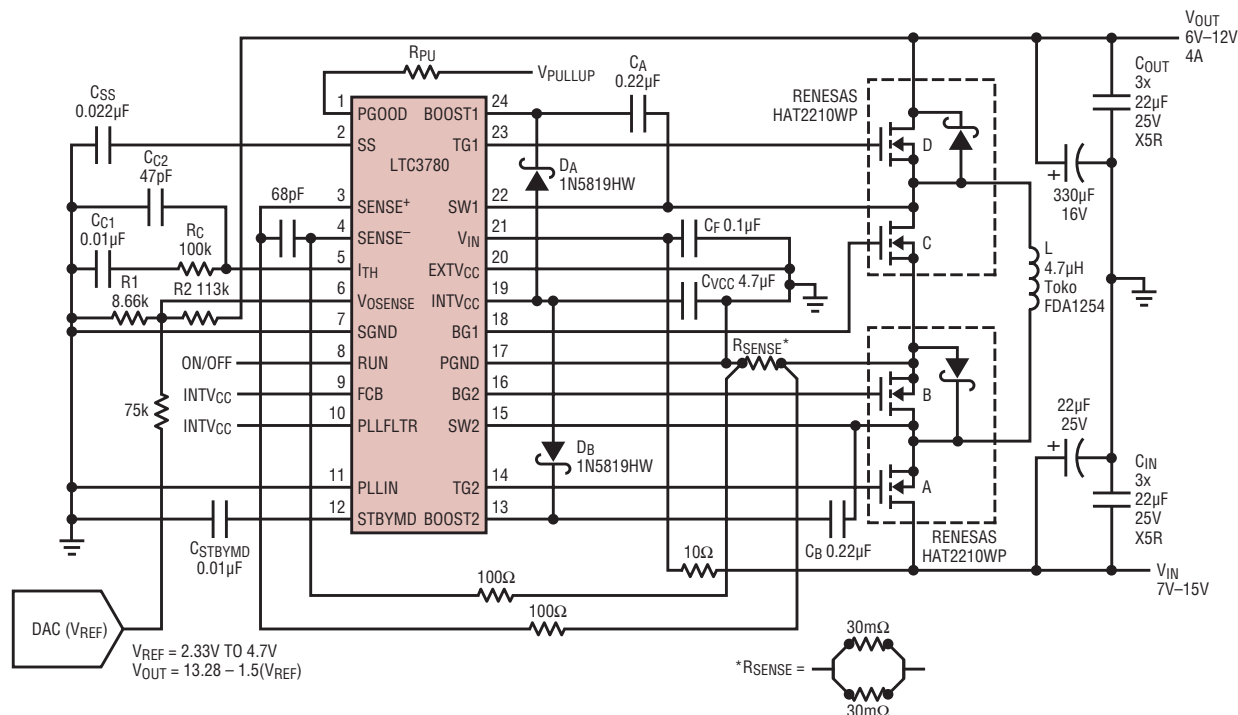
Figure 15. A compact, adjustable output supply

Dual, 1.4A and 800mA, Buck Regulator for Space-Sensitive Applications

by Scott Fritz

Introduction

The evolution of cell phones, PDAs, palmtop PCs, digital cameras, PC cards, wireless and DSL modems is one of squeezing an increasing number of features in ever-smaller devices. As features increase, so do the number of required power supplies. The problem is how to fit more supplies in less space. There are a number of solutions, including: increasing the switching frequency (allowing the use of smaller and less costly capacitors and inductors), integrating the switcher MOSFETs, or combining multiple switchers into a single package. The LTC3417 combines all of these.

A Small Package Loaded with Features

The LTC3417 is a dual synchronous, step-down, current mode, DC/DC converter designed for medium power applications. It operates from an input voltage between 2.25V and 5.5V and switches at up to 4MHz, making it possible to use capacitors and inductors that are under 2mm in height. It comes in a 3mm × 5mm, 16-lead DFN or a 20-lead TSSOP. A complete dual buck DC/DC switching regulator, using the LTC3417 in its small 16-lead DFN package, can consume less than 0.45 square inches of board real estate, as shown in Figure 1.

High Efficiency Dual Output

A typical application for the LTC3417 is shown in Figure 2. The two outputs of the LTC3417 are individually adjustable from 0.8V to 5V. V_{OUT1} can provide up to 1.4A of continuous current while V_{OUT2} can provide up to 800mA of continuous current, both at efficiencies of as high as 96%. OPTI-LOOP compensation allows the transient response to be optimized over a wide range of loads and output capacitors.
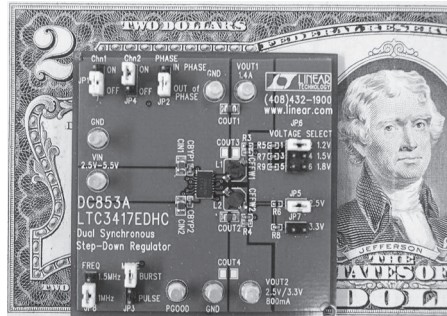

Figure 1. Dual buck regulator conserves space

Easy to Configure

The output voltages for the LTC3417 are set by the resistor dividers at the VFB pins, where the feedback voltage is compared to an internal 0.8V reference.

Major loop compensation adjustments are made with components at the ITH pins. The placement of the pole/zero combination is integral in the loop dynamics of the device, and consequently, different loop characteristics can be optimized with changes in these components, such as turn-on time, step response, and output ripple. Furthermore, the feed forward capacitor connected from V_{OUT} to VFB also helps with step response and voltage ripple. In all, the designer using the LTC3417 has exceptional control over the loop characteristics.

Constant Frequency up to 4MHz for Noise Sensitive Applications

The LTC3417 uses a current mode, constant frequency architecture that benefits noise sensitive applications—the constant frequency of the oscillator simplifies noise filtering. The frequency of operation is set using the FREQ pin. When the FREQ pin is pulled high, to V_{IN}, the internal oscillator runs at 1.5MHz. Pulling the FREQ pin low, through an external resistor, allows the user to vary the frequency anywhere between 600kHz

all the way up to 4MHz. With a 143k resistor pulled from FREQ to ground, the frequency of operation is 1MHz.

High Efficiency at Light Loads

Efficiency at light loads is important in battery-powered applications since many portable applications spend most of their time in of standby or sleep mode. The LTC3417 offers three operating modes allowing the designer to optimize light load efficiency and noise: Burst Mode operation for the highest efficiency at light loads, pulse skipping mode for high efficiency and simplified noise suppression, and forced continuous mode for noise sensitive applications. The operating mode, for both outputs, is selected through the MODE pin.

Figure 3 shows the efficiency vs load current for all three modes for the 1.4A V_{OUT1} output. Figure 4 shows the efficiency vs load current for all three modes for the 800mA V_{OUT2} output. The external components used to take the data in Figures 3 and 4 are shown in the typical application schematic of Figure 2. In all modes, with no load, the dual converter draws only 100μA. In dropout, when the output voltage is within 100mV to 200mV of the input voltage, the internal P-channel MOSFET switch is turned on continuously, thereby maximizing the usable battery life. In shutdown, when both outputs are turned off (RUN1 and RUN2 are pulled to Ground), the LTC3417 draws less than 1μA, making it ideal for low current, long battery life, applications.

Burst Mode operation achieves high efficiencies over a wide range of load currents. Burst Mode is selected for both outputs by pulling MODE to V_{IN}. In this mode gate charge losses and internal quiescent current losses are minimized at low load currents thus achieving high efficiencies over
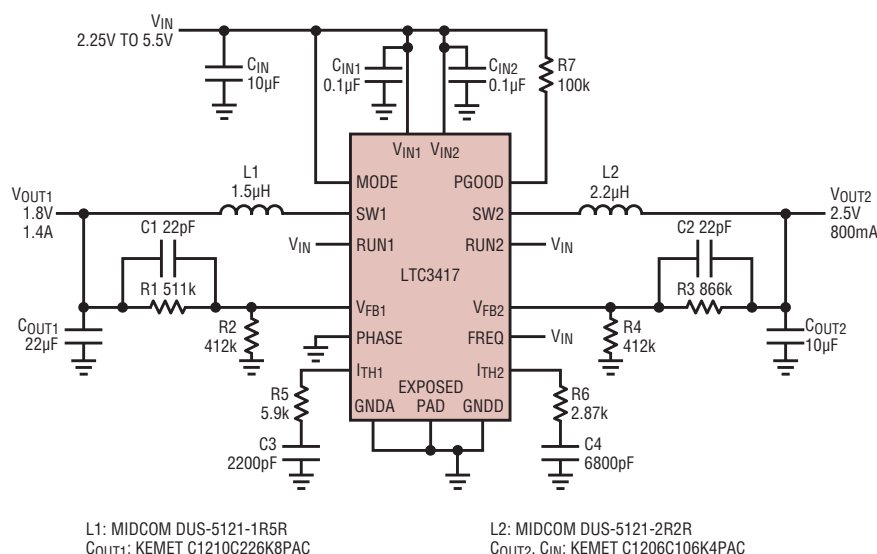
Figure 2. Dual output converter produces 1.8V at 1.4A and 2.5V at 800mA, with ceramic input and output capacitors.
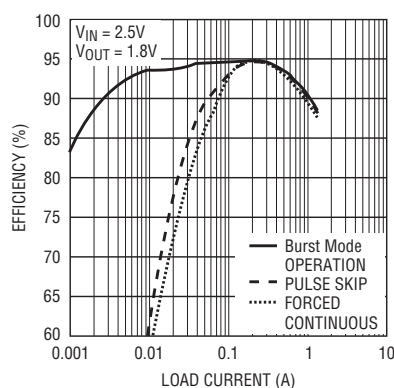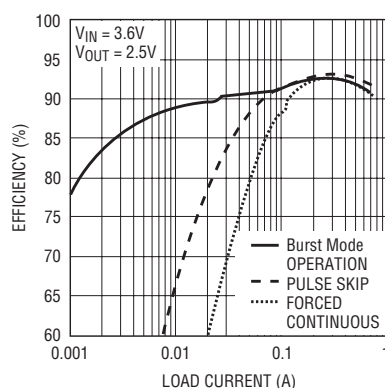

Figure 3. 1.4A V_{OUT1} Efficiency.

Figure 4. 800mA V_{OUT2} Efficiency

are controlled over a wider load current range. At lower load currents, where the output skips pulses, there can be variable frequency components in the voltage ripple, but the ripple is only around 5mV$_{P–P}$.

To reduce ripple noise even further use forced continuous mode. This mode decreases the ripple noise by sustaining the switching of the MOSFETS over all load currents, which results voltage ripple below 5mV$_{P–P}$, while trading off efficiencies at low load currents. Since the MOSFETS are always switching, the voltage ripple is constant, allowing for better filtering of the voltage ripple noise. Forced continuous mode is selected by setting the MODE pin at $V_{IN}/2$.

Out of Phase Operation Reduces Ripple and Increases Efficiency

To help reduce noise on the input voltage, and reduce the size of input capacitor, the two outputs on the LTC3417 can be selected to operate out of phase. The second output, when the PHASE pin is low, operates 180 degrees out of phase with the first channel. Out-of-phase operation produces lower RMS current on V_{IN} and thus lowers RMS derating on the capacitor on V_{IN}.

A High Efficiency 2.25V Dual Step-Down DC/DC Converter with all Ceramic Capacitors

The low cost and low ESR of ceramic capacitors make them a very attractive choice for use in switching regulators. Unfortunately, the ESR is so low that it can cause loop stability problems. Solid tantalum capacitor

a wide load current range. At low load currents, the control loop turns off all unnecessary circuitry, and stops switching for short periods of time. This generates variable frequency V_{OUT} ripple components that change with load current. Of the three modes, the output voltage ripple is highest in Burst Mode operation—up to 25mV$_{P–P}$.

Where supply noise suppression takes on more importance than efficiency, especially in telecommunications devices, pulse skipping mode can be selected by pulling the MODE pin to ground. This mode does not have the wide range of high efficiency that Burst Mode has, but the voltage ripple is minimized and the frequency components of that ripple
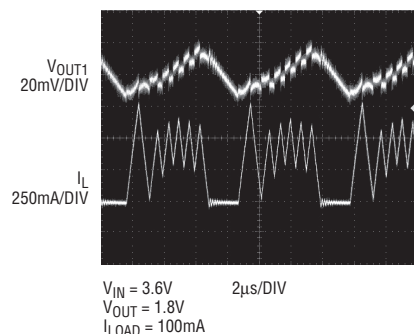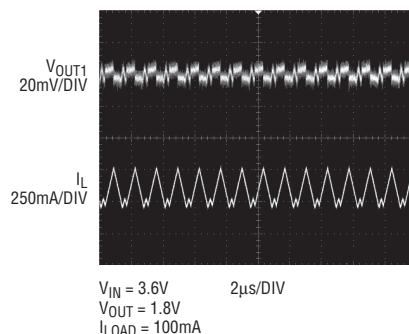

Figure 5. Burst Mode
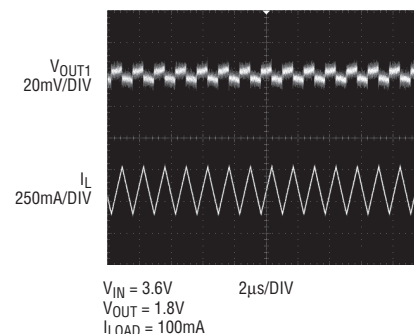

Figure 6. Pulse Skipping

Figure 7. Forced Continuous

µPower Precision Dual Op Amp Combines the Advantages of Bipolar and CMOS Amplifiers

by Cheng-Wei Pei and Hengsheng Liu

Introduction

The LTC6078 and LTC6079 are dual and quad micropower, precision op amps that combine the low offset and drift of traditional bipolar amplifiers with the low bias current of CMOS amplifiers. Additionally, the LTC6078 features low supply current and low noise, low supply voltage operation, and rail-to-rail input and output stages. This combination of features allows precision performance previously available only through composite amplifiers, manual offset trimming, or calibration.

A Superior Op Amp

Traditional bipolar op amps can be designed for excellent precision over temperature, but bipolar amplifiers lack the low bias currents of CMOS amplifiers. In high source impedance applications, a few nanoamps of input bias current can equal millivolts or more of input error, swamping the amplifier's low V_{OS}.

Traditional (and some non-traditional) CMOS amplifiers come with their own set of strengths and weaknesses. Input bias current can be much lower than their bipolar counterparts. But V_{OS} and V_{OS} drift specifications often limit the usefulness of these amplifiers in high-precision applications,

presenting the opposite problem of bipolar amplifiers. Chopper-stabilized (also known as zero drift) amplifiers, which are generally CMOS based, employ a synchronous offset cancellation scheme to negate the DC imperfections of the amplifier, so that V_{OS} and V_{OS} drift of the amplifier become almost negligible. However, zero drift

> *An LTC6078 circuit with passive high-impedance sensors can run on two alkaline AA batteries for over 1.5 years.*

amplifiers tend to draw much more current than their continuous-time counterparts, precluding their use in low-power precision applications. Additionally, zero drift amplifiers may be much noisier at higher frequencies due to auto-zero circuit clock harmonics.

The LTC6078 is a CMOS op amp with a proprietary V_{OS} trimming circuit that yields 25µV maximum V_{OS} and 0.7µV/°C maximum V_{OS} drift, lowest among all comparable bipolar and CMOS op amps. Combined with the 50pA maximum input bias current

over the entire temperature range, the LTC6078 is ideal for all precision or high-impedance instrumentation applications. The low 54µA supply current and 2.7V minimum supply voltage make the LTC6078 an excellent choice for power-sensitive or hermetically sealed circuits. An LTC6078 dual op amp circuit with passive high-impedance sensors can run on two alkaline AA batteries for over 1.5 years.

Precision Current Sense and Control

The LTC6078's rail-to-rail input and output stages allow precision input sensing right at V_{DD} or V_{SS}, which is useful for simple high-side or low-side current sensing. Figure 1 shows the LTC6078 in a simple, precise high-side current sensing application. The 25µV precision translates to excellent current resolution with a very small sense resistor, meaning more precision with less power loss. Used in a feedback loop, the LTC6078 can be used as a precision current source/sink or as a current servo.

Figure 2 shows the LTC6078 balancing the loads on two paralleled LT1763 low dropout (LDO) voltage regulators. A common practice when paralleling two voltage regulators is to simply tie the two outputs together. However, internal voltage offsets cause one regulator to handle the bulk (or all) of the load current. In the case of sink-source regulators, one may be sourcing a great deal of current *into the other regulator!*

Load sharing circuits work best when the contribution to output current is balanced between the regulators. The LTC6078 compares the voltage outputs of the two LDOs and servos the feedback pin of the second to balance them. The high
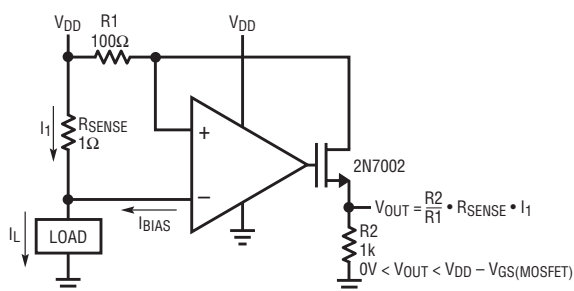

Figure 1. Precision, low-supply-voltage current sense amplifier. The LTC6078 servos the N-channel MOSFET drain current so that the voltage across R1 is the same as the voltage across the sense resistor. The precision of the LTC6078 enables a small sense resistor to be used for less power dissipation without sacrificing DC accuracy.

precision of the LTC6078 means that discrete ballast resistors are unnecessary—short pieces of wire or PCB trace are sufficient to provide the ballast resistance. With $25m\Omega$ of resistance[1], the LTC6078 can balance the current sharing of the LDOs to be within 1mA, regardless of the absolute load current output. The feedback network does not noticeably degrade the load transient performance of the regulators, and Figure 2 can be expanded to include as many paralleled regulators as necessary.

Shutdown Function

For extremely low power applications such as hermetically sealed battery-powered sensors, the 10-pin version of the LTC6078 in the tiny DFN package offers two shutdown pins (one for each amplifier). When in shutdown mode, the low 54μA per amplifier current draw is reduced to a maximum of 1μA (over the entire temperature range). The fast 50μs turn-on and 2μs turn-off times ensure that minimal power is dissipated during the transition periods.

In applications where many inputs need to be monitored and only a single analog-to-digital converter is available, the independent shutdown function of the two amplifiers allows any number of LTC6078 outputs to be multiplexed together. The high-impedance output of the LTC6078 in shutdown mode does not load the output of an active LTC6078. So long as two amplifiers are not simultaneously active, there

$0A \leq I_{OUT} \leq 1A$
LOAD MATCHING TO WITHIN 1mA WITH $25m\Omega$ OF
TRACE LENGTH (5 INCHES OF 28-GAGE STRANDED WIRE)
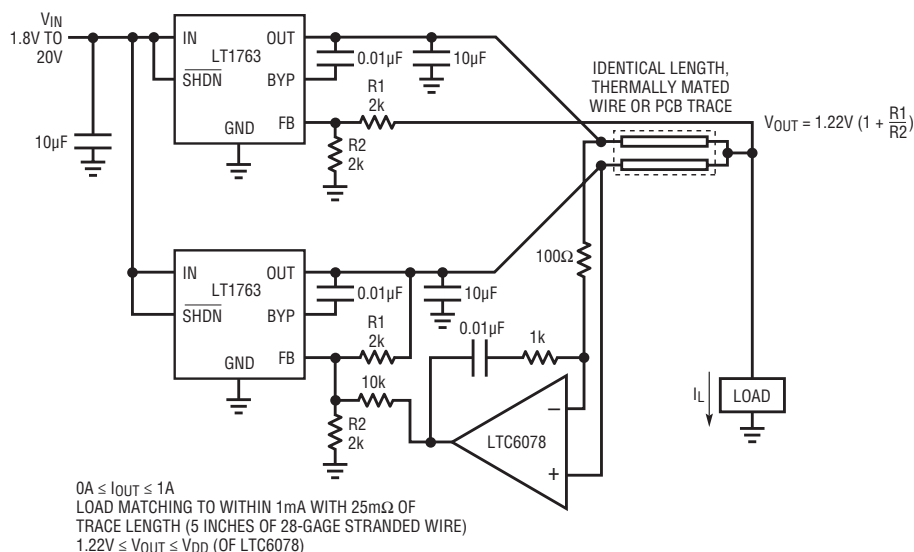$1.22V \leq V_{OUT} \leq V_{DD}$ (OF LTC6078)

Figure 2. The LTC6078 used as a current load balancing servo amplifier. Short lengths of copper wire or PCB trace can be used as ballast resistors due to the LTC6078's precision. V_{DD} of the LTC6078 may be connected to V_{IN} or V_{OUT}, as long as the minimum 2.7V supply voltage requirement is met.

is no need for external multiplexing components.

Layout Considerations

In high source impedance applications such as pH probes, photodiodes, strain gauges, et cetera, the LTC6078's low input bias current (50pA maximum over temperature) requires a clean board layout to minimize additional leakage current into a high-impedance signal node. A mere $100G\Omega$ of PC board resistance between a 5V supply trace and an input trace adds 50pA of leakage current, which is typically greater than the input bias current of the LTC6078. For comparison, a bit of unwashed soldering flux

can add a $1G\Omega–10G\Omega$ resistance. In critical applications, or if leakage is suspected, a guard ring around the high-impedance input traces driven by a low-impedance source to equal the input voltage prevents such leakage problems. The guard ring should extend as far as necessary to shield the high-impedance signal from any and all potential leakage paths. Figure 3 shows the recommended layout when using a guard ring.

Conclusion

The LTC6078 offers all of the benefits of both bipolar and CMOS amplifiers, as well as a slew of other features that make it the ultimate choice for low power, precision applications. The combination of excellent offset, drift, and input bias current specifications is unmatched among both bipolar and CMOS op amp offerings. For applications requiring four precision op amps, the LTC6079 is available in 16-pin surface-mount SSOP and DFN packages. ⊿⊤

Notes

[1] A $25m\Omega$ resistor is equal to approximately 5 inches of AWG 28 gauge copper stranded wire or 1.25 inches of a 25 mil wide one-ounce copper PCB trace at room temperature.
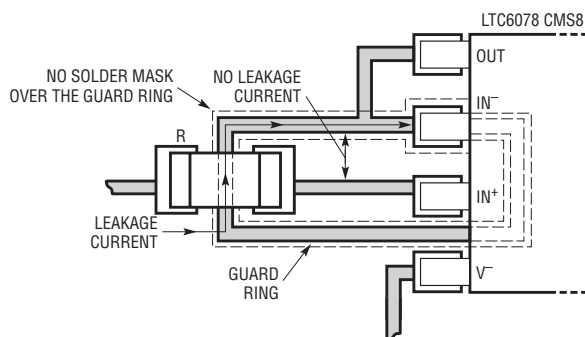

Figure 3. A sample layout using a low-impedance guard ring to shield a high-impedance signal trace from board leakage sources. The output pin can drive the guard ring directly or through a low impedance (<100kΩ) feedback resistor. The amplifier is shown in a non-inverting gain configuration.

High Voltage Micropower Regulators Thrive in Harsh Environments
by Todd Owen

Introduction

Some of the harshest environments for electronic circuits are found in industrial and automotive applications, where high, unpredictable input voltage transients, failing batteries and disconnected supplies are an expected part of doing business. A 12V car battery and a 48V industrial supply rail offer many of the same power supply design challenges. Input voltages can spike to 75V on an industrial rail or 60V during an automotive load dump. Cold cranking or overloaded lines can drop the supply voltage to only a few volts. Through all of this, the power supply must be kept alive and remain in regulation for critical circuitry, and it cannot dissipate much quiescent power—dead car batteries or lost industrial sensor data do not make for happy customers.

Tough New Regulators Provide Flexibility in Rough Environments

Three new linear regulators provide flexible options when running in these environments. The LT3012 and LT3013 provide up to 250mA at a dropout voltage of 360mV, and the LT3014 provides up to 20mA at a dropout voltage of 350mV.

$V_{\overline{SHDN}}$	OUTPUT
<0.3V	OFF
>2.0V	ON
NC	ON

Figure 1. LT3014 3.3V/20mA keep-alive supply with shutdown

The LT3012 and LT3013 offer an input voltage range of 4V to 80V and minimize power loss by running with quiescent currents of 55µA (LT3012) and 65µA (LT3013). Quiescent current is reduced to just 1µA in shutdown.

Both are stable with only a small 3.3µF capacitor on the output. Small ceramic capacitors can be used without any need for additional series resistance as is common with other regulators. The LT3013 adds a power good flag, PWRGD, to indicate that the output is above 90% of nominal, with a delay that is programmable using a single capacitor. Both the LT3012 and LT3013 are offered with adjustable outputs and a 1.24V reference voltage. The regulators are packaged in the 16-lead TSSOP and 12 pin low profile (0.75mm, 4mm × 3mm) DFN packages with exposed pads for enhanced thermal handling capability. These surface mount packages are capable of handling 1W to 3W of continuous dissipation and much higher peak transients. See the data sheet for a detailed discussion.

The LT3014 offers a 3V to 80V input voltage range, and the 7µA operating quiescent current (1µA in shutdown) makes it an attractive choice for power-critical systems. The LT3014HV is a higher voltage option of the regulator that is rated to withstand 100V transients for up to 2ms. The regulator is stable with only 0.47µF of capacitance on the output—small ceramic capacitors can be used without any need for added series resistance. It is available as an adjustable part with a 1.22V reference voltage and is packaged in the 5-lead ThinSOT and 8-lead (3mm × 3mm) DFN packages.

All of the regulators have internal protection circuitry for reverse-bat-

Part #	Output Current	Maximum Input Voltage	Dropout Voltage	Quiescent Current	Output Capacitor	Added Features
LT3014	20mA	80V	350mV	7µA	0.47µF	5-lead ThinSOT Package or 8-lead (3mm × 3mm) DFN
LT3014HV	20mA	100V (2ms Survival)	350mV	7µA	0.47µF	5-lead ThinSOT Package or 8-lead (3mm × 3mm) DFN
LT3010	50mA	80V	300mV	30µA	1µF	8-lead Thermally Enhanced MSOP Package
LT3012	250mA	80V	360mV	55µA	3.3µF	16-lead TSSOP or 12-lead (4mm × 3mm) DFN Thermally Enhanced Packages
LT3013	250mA	80V	360mV	65µA	3.3µF	All Features of the LT3012 Plus a PWRGD Flag with Programmable Delay

Table 1. Linear Technology High Voltage Linear Regulator Portfolio

tery, current limit, thermal limit, and reverse voltages from output to input. Table 1 provides a summary feature comparison of these and other high voltage linear regulators.

High Voltage Low Current Keep-Alive Regulator Application

Figure 1 shows a typical application using the low current LT3014 to provide a 3.3V keep-alive supply, such as a real-time clock, a security system, or any other system that runs constantly from a battery. The 7µA quiescent current keeps the power supply from being a significant drain on the battery.

The resistor divider is sized to match the tiny operating currents of the LT3014. Care must be exercised when operating at such low currents, since a small error can cause large percentage shifts. Insufficient cleaning of solder flux after assembly can provide resistances in the MΩ range, leading to erroneous outputs.

The $\overline{\text{SHDN}}$ pin of the LT3014 can be driven to GND by external circuitry to turn the output of the regulator off and reduce operating current. Leaving the $\overline{\text{SHDN}}$ pin open or pulling it above 2V will turn the regulator on.

The output of the LT3014 needs only the 0.47µF capacitor for stability. The regulator is designed to be stable with the widest possible range of output capacitors—the ESR of the output capacitor can be zero, as is common with small ceramic capacitors, or can be as high as 3Ω, a value found more often with small tantalum or aluminum electrolytic capacitors. The minimum output capacitor coupled with the micropower nature of the LT3014 tends to give larger voltage deviations with fast transients, so larger values are recommended if there are large current steps.

Higher Output Current Supply with PWRGD Flag

When higher output currents are needed, Linear Technology offers several options. The LT3010 regulator can provide 50mA of output current at a maximum dropout of 300mV and

Figure 2. LT3013 5V/250mA supply provides PWRGD flag

a maximum input voltage of 80V. If a higher output current is needed, the LT3012 and LT3013 are now available. Figure 2 shows a 5V supply that can provide up to 250mA of current using the LT3013. This supply operates at only 65µA quiescent current and requires only 3.3µF of capacitance on the output. An added feature that this part has is a PWRGD flag that indicates when the ADJ pin is within 10% of its nominal voltage of 1.24V.

The PWRGD flag of the LT3013 can be used to provide a microprocessor reset signal or other logic flag. Figure 3 shows the block diagram for the PWRGD flag. The PWRGD pin is an open-collector output, capable of sinking 50µA when the output is low; there is no internal pull-up on the PWRGD pin, an external resistor must be used. When the output rises to within 10% of its final value, a JK flip-flop allows a 3µA current source to begin charging the capacitor on the CT pin. As the CT pin reaches its trip level (approximately 1.6V at 25°C), the 3µA current is shunted away to clamp the capacitor voltage and set the PWRGD flag state to high impedance.

During normal operation, an internal glitch filter ignores short transients (<15µs) on the output voltage. Longer

transients below the 10% low threshold will reset the internal JK flip-flop. This flip-flop ensures that the capacitor on the CT pin is fully discharged to the $V_{CT(LOW)}$ threshold before re-starting the time delay. This is done to provide a consistent time delay after the output returns to within 10% of its regulated voltage before the PWRGD pin switches to the high impedance state.

If the PWRGD function of the LT3013 is not needed for your application, the LT3012 can be used to provide the same regulator performance. The removal of the PWRGD circuitry allows the LT3012 to operate at a lowered quiescent current of 55µA.

Conclusion

Three new regulators satisfy the needs of tough automotive and industrial electrical environments. A range of possible output currents and quiescent currents allow designers to pick a solution that can limit power dissipation during normal operation while still providing the capability to handle high voltage transients. The most important feature of these devices is that they can withstand the rigors of the worst electrical environments, thus ensuring a steady power supply for critical circuits. ∠T
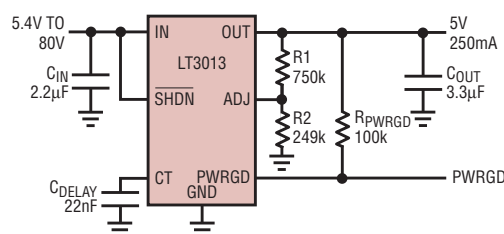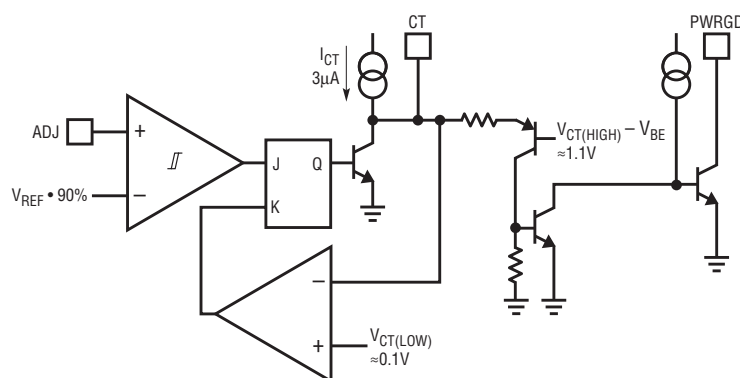

Figure 3. PWRGD circuit block diagram

Complete 2-Cell-AA/USB Power Manager in a 4mm × 4mm QFN

by G. Thandi

Introduction

One of the most popular battery solutions for consumer handheld devices is the venerable two-cell AA (alkaline or nickel-metal hydride) source, especially in GPS navigators, digital cameras and MP3 players. AA batteries are readily available, relatively low cost and offer high power density. Many of these same portable devices supplement battery power with plug-in wall adapter and offer a USB bus (for data transfer). The USB bus can also be used to provide power. The problem is how to seamlessly switch between these three disparate types of supplies: 2-cell AA, wall and USB. The solution is the LTC3456.

The LTC3456 is a complete system power IC that seamlessly manages power flow between an AC wall adapter, USB and 2-AA battery, while complying with USB power standards—all in a 4mm × 4mm QFN package (Figure 1). The device generates two separate power rails: a 3.3V (fixed) main supply and a 1.8V (adjustable) core supply. In addition, the
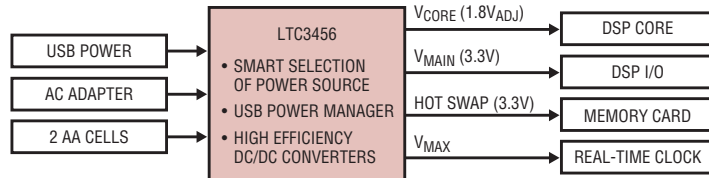
Figure 1. The LTC3456 is a complete system power management IC available in a tiny 4mm×4mm package.

LTC3456 contains a fully featured USB power manager, a Hot Swap output for powering memory cards and an un-

> *The LTC3456 squeezes a USB power manager, four high efficiency DC-DC converters, a Hot Swap controller, a low-battery indicator and much more into a 4mm × 4mm QFN package.*

committed gain block suitable for use as a low-battery comparator or an LDO controller. The device also generates an always-alive V_{MAX} output, suitable

for supplying power to critical blocks like the real time clock, which needs to stay alive even during shutdown.

About the LTC3456

The LTC3456 contains four high efficiency 1MHz fixed frequency switching regulators that operate with efficiencies up to 92%. Figure 2 shows a typical LTC3456 application. Most processors used in portable applications require dual power supply voltages. These voltages can be 3.3V for the I/O circuitry and 1.5V or, 1.8V for the processor core. Additionally, the processor might require that the power supplies startup in a specific sequence to prevent processor latch

Figure 2. A LTC3456-based, complete power solution, including a 1.8V output for processor core, a 3.3V output for the I/O, a 3.3V Hot Swap supply for the memory card and a V_{MAX} output for RTC. This design uses all ceramic capacitors with minimal parts count.

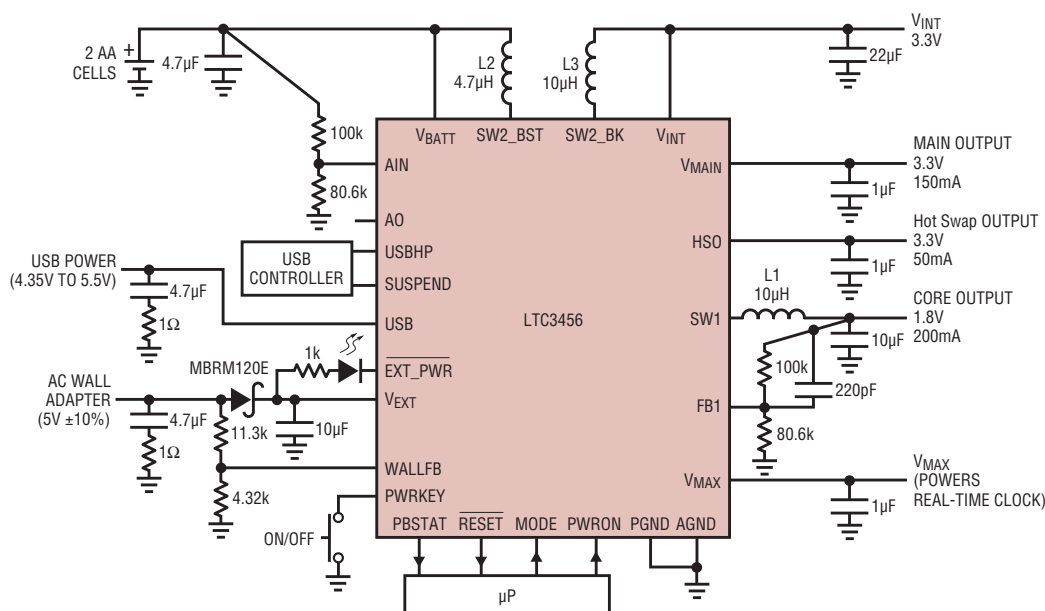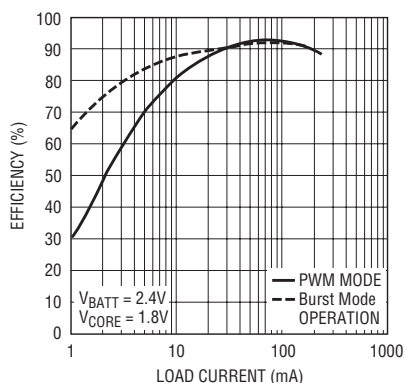Figure 3. Core converter efficiency for Figure 2's circuit. LTC3456 is powered from the battery. Efficiency is shown for both PWM and Burst Mode operation.
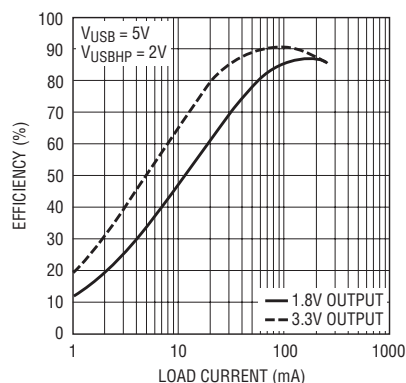

Figure 4. Core and Main converter efficiency for Figure 2's circuit. The LTC3456 is powered from the USB with the USB current limit set at 500mA (USBHP = High).

up or improper initiation. Usually the core supply must come up before the I/O supply.

The LTC3456 has in built power supply sequencing for the core and main outputs. At power-up, the V_{INT} output, a fixed 3.3V supply, is the first one to power up. It supplies power to most of the internal circuitry. The amount of external loading at this output should be limited (Refer to the LTC3456 datasheet for more details). The core output, adjustable from 0.8V to 1.8V, comes up next followed by the V_{MAIN} output. The V_{MAIN} output, a fixed 3.3V supply, powers up with a delay of 0.8ms (typ) after the core output comes into regulation. The V_{MAIN} output is generated from the V_{INT} output through an internal 0.4Ω (typ) PMOS switch and can be used to power the I/O circuitry. The 0.8ms delay gives sufficient time to the processor to stabilize the system clock and load internal registers before the peripheral circuitry powers up.

The LTC3456 produces a Core output, adjustable from 0.8V to 1.8V suitable for powering new low voltage processors (ARM and others). The LTC3456 control scheme allows 100% duty cycle operation for the core output. It provides low dropout operation when the core output is powered from the battery, thereby extending battery life. Both Main and Core converters offer Burst Mode operation (MODE Pin selectable) when powered from the battery resulting in high efficiency at light loads as seen in Figure 3. The Core converter features greater

than 92% efficiency when powered from the battery. Burst Mode operation is disabled when powered from USB/wall power. Figure 4 shows the system efficiency when powered from the USB. The Main converter achieves up to 90% efficiency when powered from the USB.

The LTC3456 has a built-in Hot Swap output suitable for powering flash memory cards. The Hot Swap output features short-circuit and reverse voltage blocking capability. It allows memory cards to be hot swapped into and out of the system. It has a built-in 120mA(typ) current limit suitable for powering flash memory cards.

The LTC3456 features short-circuit protection for both the main and core outputs. It also provides output disconnect for all the outputs with the exception of the V_{MAX} output. The Core, Main and Hot swap outputs are

all discharged to ground in shutdown. The V_{MAX} output is the highest of the V_{BATT}, V_{INT}, V_{EXT} and USB voltages. This output can be used to supply a maximum of 1mA output current. The V_{MAX} output stays alive even when the IC is in shutdown and is suitable for supplying power to critical system blocks like a real time clock.

PowerPath Control

The LTC3456 contains a proprietary PowerPath control scheme that seamlessly switches over the system power from a 2-AA battery to USB/wall Power and vice versa. Figure 5 shows a simplified block diagram of the internal power-path. The AC adapter and the USB bus supply power to the switching regulators via the V_{EXT} pin. The LTC3456 contains a full featured USB power manager to control the flow of power from the USB pin via the state of the USBHP and SUSPEND pins. The current through the USB pin is accurately limited to 100mA or, 500mA depending on the state of the USBHP pin. All USB functionality can be disabled by pulling the SUSPEND pin high.

DC-DC conversion is a particularly challenging task when the 2 AA battery voltage (1.8V to 3.2V) must be boosted to generate 3.3V output, and the USB/wall power (4V to 5.5V) must be stepped down to generate the same voltage. The LTC3456 accomplishes this task via the BOOST and BUCK2 converters. This is the most efficient
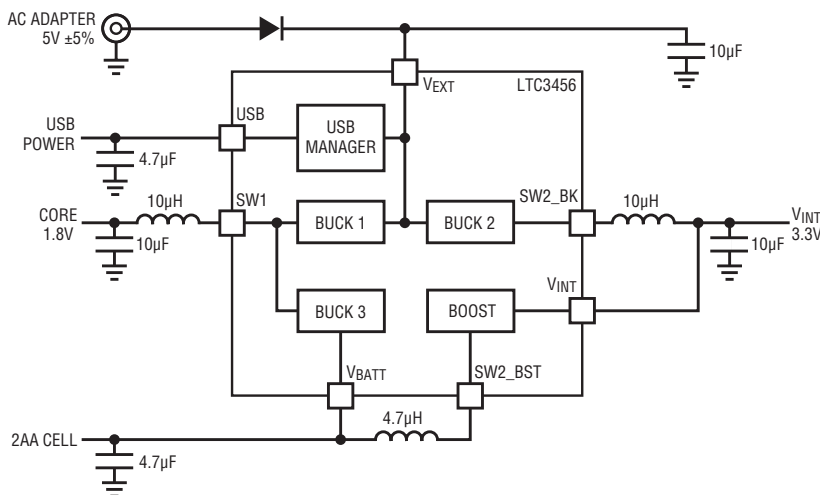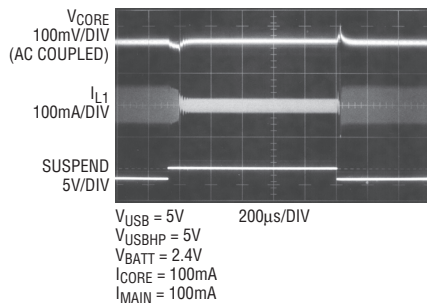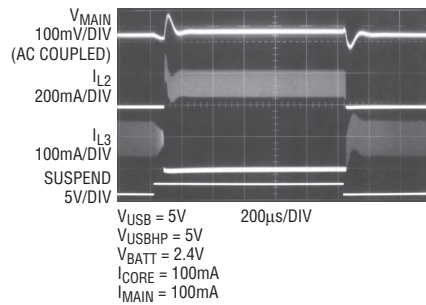

Figure 5. LTC3456's simplified block diagram showing internal PowerPath.

V_CORE 100mV/DIV (AC COUPLED)
I_L1 100mA/DIV
SUSPEND 5V/DIV

V_USB = 5V   200μs/DIV
V_USBHP = 5V
V_BATT = 2.4V
I_CORE = 100mA
I_MAIN = 100mA

a. Core output transient waveforms

V_MAIN 100mV/DIV (AC COUPLED)
I_L2 200mA/DIV
I_L3 100mA/DIV
SUSPEND 5V/DIV

V_USB = 5V   200μs/DIV
V_USBHP = 5V
V_BATT = 2.4V
I_CORE = 100mA
I_MAIN = 100mA

b. Main output transient waveforms

Figure 6. USB and 2AA Battery power supply switchover waveforms for Figure 2's circuit. The USB power is disconnected when the Suspend pin is taken high. Main and core outputs both exhibit less than ±2% total deviation at the time of switchover.

V_PWRON 5V/DIV
V_MAIN 5V/DIV
V_CORE 2V/DIV
$\overline{RESET}$ 5V/DIV

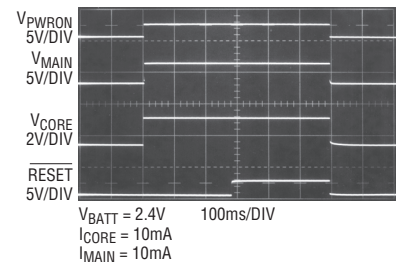V_BATT = 2.4V   100ms/DIV
I_CORE = 10mA
I_MAIN = 10mA

Figure 7. Power-up and power-down waveforms for Figure 2's circuit. Both V_MAIN and V_CORE outputs are discharged to ground during shutdown. Power-on reset ($\overline{RESET}$) is held low for a delay of 262ms after V_CORE comes into regulation.

way of generating the 3.3V power rail. The LTC3456 achieves efficiency greater than 90% when generating 3.3V output from the battery or USB/wall adapter. The core output (1.8V) is generated via BUCK1 (USB/wall Powered) and BUCK3 (Battery Powered) converters. The unique topology of LTC3456 generates the 1.8V rail via a single inductor resulting in a cost and space saving. It achieves efficiency greater than 92% when generating the 1.8V output from the battery. The various operational modes of LTC3456 are summarized in Table 1.

Portable devices are required to seamlessly switch-over from the battery power to USB or wall power and vice versa to ensure smooth system operation. As an example, a user is playing music on a portable MP3 player with the USB cable connected. If the USB cable is suddenly yanked off the device, the user should be able to continue listening to the music without any interruption. The LTC3456 makes it possible through seamless switchover of system power.

Figure 6 shows USB and 2-AA battery power supply switchover waveforms for Figure 2's circuit. The USB power is unavailable when the Suspend pin is taken from low to high. Main and core outputs both exhibit less than ±2% total deviation at the time of switchover making the switchover seamless to the processor core and the peripheral circuitry.

Easy Interfacing with a Microprocessor

The LTC3456 simplifies the task of interfacing with a micro-processor. The PWRON, PWRKEY, PBSTAT and $\overline{RESET}$ pins provide all the required system information to the processor and simplify power sequencing. The PWRON, PWRKEY and PBSTAT keys simplify the task of orderly powering-up and shutting down the IC. The datasheet contains the timing diagram and gives detailed information about their operation.

The LTC3456 also contains power-on reset circuitry (accessed via pin $\overline{RESET}$) that is active during both

power-up and shutdown. The power-on reset is required to hold the processor in its reset state at power-up and it must keep the processor from starting operation until all system power supplies have stabilized. The LTC3456's built in power-on reset circuitry monitors both the V_INT (3.3V) and Core (1.8V) voltages and interfaces to the processor via the $\overline{RESET}$ pin. The $\overline{RESET}$ pin is held low during initial power-up. When both the Main and Core outputs come into regulation, a reset delay timer gets activated. There is a full 262ms timeout before $\overline{RESET}$ is released and the processor is allowed to come out of reset and begin operation. The timeout delay of 262ms gives sufficient time for the processor to initialize the internal registers/RAMs. During power-off the $\overline{RESET}$ pin is again pulled low. This prevents the micro-processor from entering into any random operational modes.

Figure 7 shows the power-up and power down waveforms for the circuit of Figure 2 in battery powered mode. The $\overline{RESET}$ circuitry works similarly

Table 1. Summary of LTC3456 PowerPath operational modes and features

| AC ADAPTER	USB POWER	2 AA CELLS
Highest priority for powering the IC	Medium priority for powering the IC	Lowest priority for powering the IC
Battery loading < 2μA	Battery loading < 2μA	Burst Mode operation (User Selectable) conserves battery energy
Internal soft-start circuitry limits current drawn from the adapter at start-up	USB pin current accurately limited to 100mA or 500mA	Battery inrush current regulated during power-up. Additionally, internal soft-start limits input current at start-up.
AC adapter (min) voltage set via the WALLFB Pin	USB (min) voltage set to 4V	Battery (min) voltage indicator set via the AIN Pin
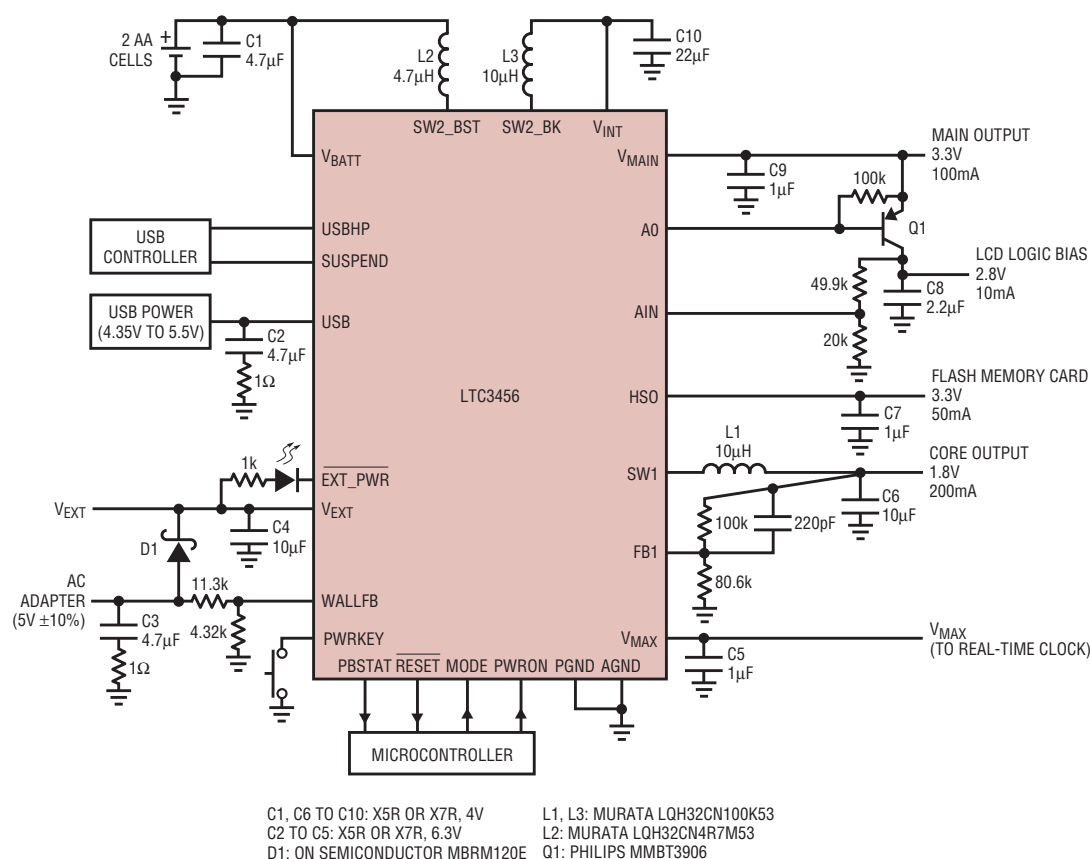
Figure 8. A 2-AA-cell-powered, complete power supply for GPS navigation system. Note that the uncommitted gain block (Pins AIN and AO) is configured as an LDO controller to generate an auxiliary 2.8V output.

when battery or externally powered. The $\overline{\text{RESET}}$ pin is held low for a delay of 262ms after V_{CORE} comes into regulation. When the IC is shut-down, both V_{MAIN} and V_{CORE} outputs are disconnected from the input power and discharged to ground This prevents the outputs from being stuck in an indeterminate logic-level state and adversely affecting the operation of the microprocessor. It also ensures that the outputs rise in a predictable fashion during power-up.

Voltage Monitoring

The LTC3456 has an on-chip gain block that can be used for low-battery detection, with the low battery trip point set by two resistors (Figure 2) at the AIN pin. The nominal voltage at AIN is 0.8V. The AO pin is an open-drain logic output that sinks current whenever the voltage at the pin AIN falls below 0.8V. The gain block can also be configured to drive an external PNP or PMOS transistor to generate an auxiliary voltage.

In addition, the LTC3456 has on board voltage comparator circuitry to detect the presence of USB or wall power, with a status output at the $\overline{\text{EXT\_PWR}}$ pin. The open-drain logic output of $\overline{\text{EXT\_PWR}}$ is capable of sinking up to 5mA, suitable for driving an external LED. The on-board voltage detectors continuously monitor the status of the USB voltage and AC adapter voltage (via the WALLFB Pin). Whenever the USB or, wall power is available and in regulation, the $\overline{\text{EXT\_PWR}}$ pin is pulled low.

Portable GPS Navigator Power Supply

Today's portable GPS navigators run off two AA batteries or an AC adapter and come equipped with a USB bus (for data transfer). Long battery life and small system size are the key requirements for the power supply. The microprocessor used in GPS navigators usually require at least two different voltage supplies: typically 3.3V for the I/O circuitry and 1.5V or

1.8V for the processor core. The navigator might also require an auxiliary 2.8V supply voltage to bias the LCD display controller IC.

Figure 8 shows a complete, compact and efficient power supply for a portable GPS navigator. The V_{MAIN} (fixed 3.3V) provides power to the I/O circuitry. The power supply for the processor core, V_{CORE}, is set at 1.8V and can be adjusted by changing the feedback resistor ratio. The 3.3V Hot Swap output powers flash memory cards. The LTC3456 contains an uncommitted gain block (Pins AIN and AO) that can be used as a low-battery indicator or an LDO controller. The circuit in Figure 8 shows the gain block being used as an LDO with an external PNP to generate an auxiliary 2.8V output voltage from the Main output. The auxiliary 2.8V supply is being used to power an LCD controller IC. The V_{MAX} output of the LTC3456 stays alive even in shutdown and is used to supply power to a real-time clock. *continued on page 19*

Micropower Precision Oscillator Draws Only 60µA at 1MHz by Albert Huntington

Introduction

Traditionally, electronic clocks use quartz crystals, ceramic resonators, or discrete R, L or C elements as a timing reference, but each of these designs has several drawbacks that make them unsuitable for a variety of applications. Quartz crystals and ceramic resonators can be power-hungry, and their accuracy is subject to environmental stress. Crystal oscillators have the additional disadvantage of being susceptible to damage from shock or vibration. RC oscillators have poor jitter and accuracy, or require expensive precision components. A more robust, and compact alternative to all of these is an all silicon clock, such as the LTC6906 micropower, resistor-controlled oscillator.

The LTC6906 is a monolithic silicon oscillator with significant size, power, cost and environmental sensitivity advantages over other oscillators, and it requires only a single external resistor to set the frequency over its full range of 10kHz to 1MHz (Figure 1). Its 0.65% accuracy and jitter as low as 0.03% make it an excellent choice for precision applications, and the power and size advantages let the LTC6906 fit in designs where a crystal oscillator could never go.

Device Description

The LTC6906 is a part of Linear Technology's line of resistor controlled SOT-23 oscillators. These resistor controlled oscillators use a single inexpensive external resistor to accurately set the oscillator frequency, and there is a simple linear relationship between the resistor value and the output frequency.

The LTC6906 uses an innovative low power architecture with a master oscillator running between 100kHz and 1MHz. A three state, divide pin is provided which can engage an internal divider to decrease the output frequency by a factor of 1, 3 or 10

to provide a total frequency range of 10kHz to 1MHz. For increased accuracy at the lower end of the frequency range with very low bias currents, a guard pin is provided for the frequency setting resistor input.

The master oscillator frequency is set by an external resistor connected between the SET pin and ground. The LTC6906 maintains the SET pin at approximately 650mV above ground, with a tempco of –2.2mV/°C. The master oscillator frequency is related to the SET resistor by:

$$f_{MASTER} = 1MHz \bullet \left(\frac{100k\Omega}{R_{SET}} \right),$$

and is related only to the resistance on the SET pin, without regard to the exact SET pin current or voltage.

Low Power Dissipation

The LTC6906 uses only 10µA when running at 100kHz (Figure 2). There are three components to this current draw. A static bias current of about 5µA is used by the internal reference and bias circuits. A variable bias current of about 6 times the current in the SET resistor is used to power and bias the internal oscillator. A load current related to the load capacitance, power supply voltage and load resistance makes up the remainder of the dissipation equation. An approxi-
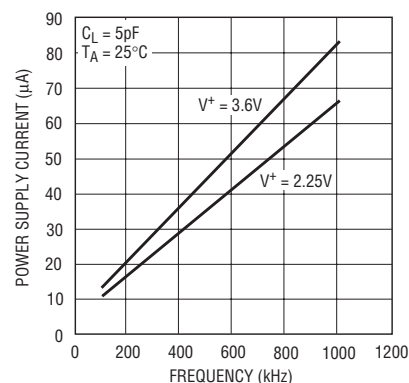

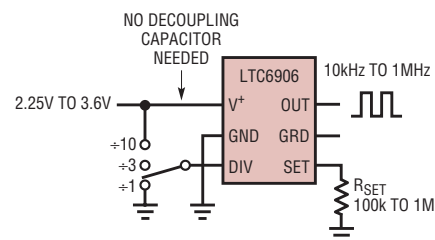**Figure 1. The LTC6906 requires only a single external resistor.**

mate expression for the total supply current is:

$$I_{SUPPLY} = 5\mu A + 6 \bullet I_{SET} +$$
$$\left[V^+ \bullet F_{OUT} \bullet (C_{LOAD} + 5pF) + \frac{V^+}{2 \bullet R_{LOAD}} \right].$$

Figure 3 shows the relative magnitudes of these three components over the frequency range in the case of a load capacitance of 5pF, with no resistive load.

Note that power dissipated in the load ranges from 25% to over 40% of the total power from 100kHz to 1MHz operation. Any lessening in the load capacitance or resistance can have dramatic effects on the load current portion of the power supply dissipation. Power dissipation as low at 7µA at 100kHz is achievable with light output loading. Decreasing the power supply voltage also reduces the power dissipated into the load.

Figure 2. The LTC6906 has extremely low power dissipation.
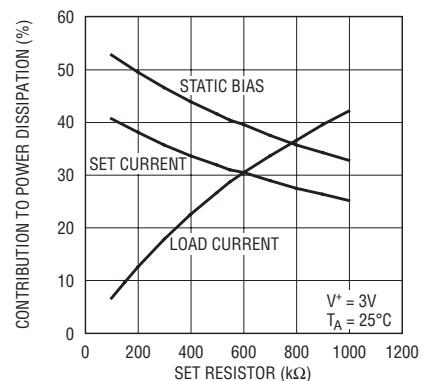

Figure 3. Percentage contributions to power dissipation of static bias, set current and load currents. Data was taken at 3V, 25ºC ambient temperature.

Engaging the internal divider has larger effects on power dissipation where the load current is higher at higher frequencies, but little effect where the internal bias currents dominate at lower master oscillator frequencies, as illustrated in Figure 4.

Choosing a SET Resistor

The choice of a SET resistor is guided by the desired frequency output. The part is specified for master oscillator frequencies between 100kHz and 1MHz, with possible DIV ratios of 1, 3 and 10. These DIV ranges overlap, and some frequencies have multiple valid combinations of DIV and SET resistor values. The lowest power dissipation for a given frequency is always obtained by setting the SET resistor as high as possible and DIV as low as possible. Generating 100kHz using DIV = 10 and R_{SET} = 100kΩ dissipates much more power than using DIV = 1 and R_{SET} = 1000kΩ.

The following equation relates the desired master oscillator frequency to the R_{SET} value:

$$R_{SET} = \frac{1M\Omega}{N} \bullet \frac{100kHz}{F_{OUT}};$$

where N is the divider ratio chosen of 1,3 or 10, R_{SET} is the SET resistor value and f_{OUT} is the desired output frequency. For example, see Table 1 for valid R_{SET} values to generate a 100kHz output frequency at the three DIV settings. It is apparent from the table that, depending on the DIV pin setting, the current for a particular output frequency could vary by a factor of up to 4.5.

There are tradeoffs to choosing the largest possible SET resistor and the smallest possible value of DIV. Jitter increases at the smaller DIV values, and frequency accuracy may suffer

Table 1. R_{SET} values for 100kHz

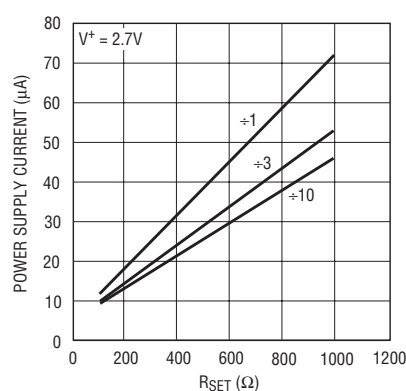| Divider Setting N	R_{SET} Value	Approximate Supply Current
1	1MΩ	10µA
3	333.33KΩ	20µA
10	100kΩ	45µA

Figure 4. The LTC6906 power supply current vs DIV pin setting. All data taken at 3V supply, 5pF load.

more with high RSET values due to leakage at the SET pin, especially at higher temperatures.

Layout Considerations

The LTC6906 is capable of frequency accuracy of <0.65% over the commercial temperature range, and for best accuracy, care must be exercised to limit board leakage around the R_{SET} pin. A 1GΩ parasitic resistance to ground can change the frequency by 0.1%, and the same resistance to the positive supply could increase that to 0.3%. A guard pin which is weakly driven to the same DC voltage as the SET pin has been provided, and the guard signal should be routed completely around the SET pin, on the same side of the PC board as the device, and should have no soldermask (see Figure 5).

The guard ring is not be necessary in all applications, especially those with lower values of SET resistor and excellent assembly practices. The majority of board leakage problems occur due to insufficient cleaning of flux from the board or from sloppy assembly. With perfectly clean assembly, the guard ring is completely unnecessary.

The LTC6906 uses a switched current to drive the SET resistor, so there may be some noise visible on the SET line. Although this noise does not contribute to jitter on the output signal, it can influence the frequency accuracy in the presence of parasitic capacitance on the SET pin. Because of this sensitivity to parasitic capacitance and because of the danger of

additional leakage from long traces, it is recommended that the SET resistor be located as close as possible to the SET pin, and on the same side of the PC board as the LTC6906.

Long Term Drift of Silicon Oscillators

Long-term stability of silicon oscillators is specified in ppm/√kHr, which is typical of other silicon devices such as operational amplifiers and voltage references. Because drift in silicon-based oscillators is generated primarily by movement of ions in the silicon, most of the drift is accomplished early in the life of the device and the drift can be expected to level off in the long term. The ppm/√kHr unit models this time variant decay. Crystal oscillators are occasionally specified with drift measured in ppm/year. This measurement models a different drift mechanism, and the decay profile is not the same. A comparison of various drift rates over a five year time period is shown in Figure 6.

When calculating the amount of drift to be expected, it is important to consider the entire time in the calculation, because the relationship to time is not linear. The drift for 5 years is not 5 times the drift for one year. A sample calculation for drift over 5 years at 300ppm/√kHr is as follows:

5 years • 365.25 days/year • 24 hours/day
= 43,830 hours = 43.830kHr

$$\sqrt{43.830kHr} = 6.62\sqrt{kHr}$$

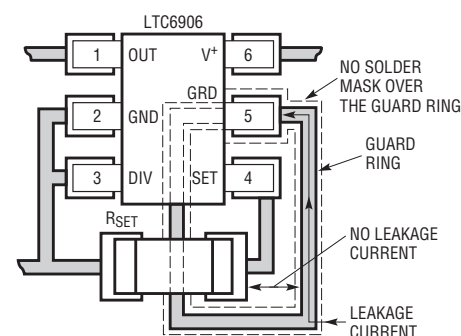$$6.62\sqrt{kHr} \bullet \frac{300ppm}{\sqrt{kHr}} = 0.198\% \text{ over 5 years}$$

Figure 5. The GRD ring should be routed on the same side of the PC board as the LTC6906, and should have the solder mask removed.
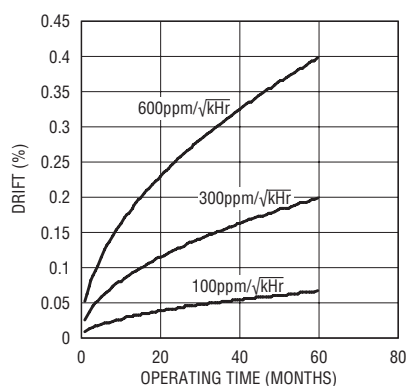
Figure 6. Comparison of 5-year drift at 100ppm/√kHr, 300ppm/√kHr and 600 ppm/√kHr

Drift calculations assume that the part is in continuous operation during the entire time period of the calculation. The movements of ions which results in drift is usually aided by electric fields in the operating parts, and drift is substantially lower if the parts are not powered up during the entire period of drift. Conservative calculations would use a tenth of the drift specification for time when power is not applied to the part.

Switching the DIV Pin

The DIV input pin on the LTC6906, similar in many ways to the DIV pin on other LTC silicon oscillators, is a three state input, capable of resolving three different states: high, open and low. Three state input pins allow greater functionality in low pin-count packages, and are compatible with the tri-state outputs of many microcontrollers. Static configuration is easily accomplished by tying the pin to either the positive supply or ground, or leaving it floating.

In the OPEN state, the DIV pin of the LTC6906 is reasonably immune to noise commonly found on PC boards, but care should be taken to avoid routing a long floating trace off the pin, or

routing the pin driving that trace next to a line with strong AC signals. The noise immunity of the DIV pin can be easily improved by adding a capacitor to ground, or a series resistor of up to 100kΩ placed near the DIV pin.

In normal operation, the DIV pin uses a small current of about 1µA to pull the DIV pin voltage close to half of the power supply voltage. Therefore, if the pin is left open, any extra capacitance on the pin slows its settling to the OPEN state.

Applications that use the DIV pin to switch frequency in real time need to take into account that, because it is designed for low power operation, the DIV pin buffer circuit is slow, with delays up to around 12µs between activation of the DIV pin and changes in the output of the LTC6906. This switching delay must be accounted for in the application, or an external frequency divider can be substituted for the internal frequency divider in order to decrease the frequency change response time.

Manipulating the SET Pin

The LTC6906 can be configured in applications where the SET resistor needs to be changed for operation at different frequencies. When changing the SET resistor, best performance and accuracy is obtained by placing the switching mechanism between the set resistor and GND, not between the set resistor and the SET pin (see Figure 7).
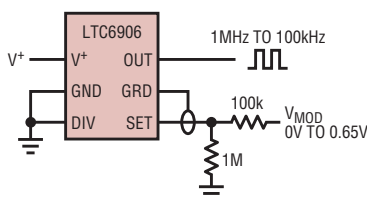

Figure 8. Modulating the SET pin current through a resistor provides greater immunity to noise coupling.
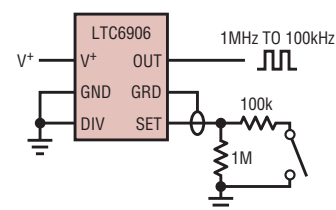

Figure 7. Switching in different SET resistors

The SET pin is sensitive to interference from external capacitance or signals, and isolation through the SET resistor reduces this sensitivity.

The LTC6906 is not ideally suited to current modulation through the SET pin because in order to save power, the voltage on the SET pin is not regulated over temperature or load. This results in the modulation of the frequency being a function of the set pin voltage as well as the set pin current. The frequency can still be modulated through the SET pin, but the relationship between the modulation current or voltage and the output frequency is not very accurate since it depends on the poorly defined SET pin voltage.

The circuit in Figure 8 shows a modulation method that results in low jitter and stable performance. By modulating the SET pin current through a resistor, the effects of parasitic capacitance on the initial frequency accuracy are reduced.

Conclusion

The LTC6906 is a micropower oscillator with 0.65% accuracy and very low jitter. Its small size, simple configuration and extremely low power consumption make it ideal for low power applications driving microcontrollers, FPGAs and providing a clock reference for battery powered devices. *LT*

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Conclusion

The LTC3456 is a complete system power management IC that seamlessly manages power flow between an AC adapter, USB cable and 2-AA battery supply. A host of features, including

an integrated USB power manager, high efficiency DC-DC converters, a Hot Swap controller and a Low-Battery Indicator, are squeezed into a 4mm × 4mm QFN package. The external components count and overall system

cost are minimized. Simplicity, design flexibility, a high level of integration and small size makes LTC3456 an ideal choice for powering many portable USB devices. *LT*

New Standalone Linear Li-Ion Battery Chargers

by Alfonso Centuori

Introduction

Rechargeable batteries are commonly used to power portable devices such as digital cameras, PDAs, mobile phones and MP3 players. A wall adapter is the most common source of charging power, but an increasing number of applications are tapping into available USB power. The LTC4061 and LTC4062 are specifically designed to charge single-cell lithium-ion batteries from either of these sources.

Both devices use constant current/constant voltage algorithms to deliver up to 1A of charge current (programmable) with a final float voltage accuracy of ±0.35%. They include an internal P-channel power MOSFET and thermal regulation circuitry with no blocking diode or external sense resistor required—the basic charger circuit requires only two external components.

The LTC4061 and LTC4062 include both programmable time and programmable current based charge termination schemes. The open-drain charge status pin, $\overline{\text{CHRG}}$, can be programmed to indicate the state of the battery charge according to the needs of the application. The LTC4061 provides an AC Power open-drain status pin, $\overline{\text{ACPR}}$, to indicate that enough voltage is present at the input to charge a battery. Additional safety features designed to maximize battery lifetime and reliability include Negative Temperature Coefficient, NTC, battery temperature sensing (LTC4061) and the SmartStart™ charging algorithm, which extends the lifetime of the battery by preventing unnecessary charge cycles.

In the LTC4062, a low I_q precision comparator replaces the NTC and $\overline{\text{ACPR}}$ functions of the LTC4061. Without input power applied, the LTC4062 internal low power comparator can function while drawing just 10µA from the battery. With input power applied, LTC4061 and LTC4062 can

Figure 1. LTC4061 and LTC4062 USB/wall adapter power Li-Ion charger configuration using charge current termination

be put into shutdown mode to reduce the supply current to a very low value (20µA) and the battery drain current to less than 2µA.

Internal thermal feedback regulates the charge current to maintain a constant die temperature during high power operation or high ambient temperature conditions.

Programmability

The LTC4061 and LTC4062 provide a great deal of design flexibility including programmable charge current and programmable total time termination or programmable current termination. The maximum charge current is programmed using a single resistor from the PROG pin to ground. The charge current out of the BAT pin can be determined at any time by monitoring the PROG pin voltage and applying the following equation:

$$I_{BAT} = \frac{V_{PROG}}{R_{PROG}} \bullet 1000$$

A current detection threshold, I_{DETECT}, is set by connecting a resistor, R_{DETECT}, from IDET to ground. This threshold is used to change the state of the $\overline{\text{CHRG}}$ pin indicating that a battery is nearly full. Alternatively, this threshold can be used as the termination current threshold completing the charge cycle.

When using total time termination, the charge time is set by connecting a capacitor, C_{TIMER}, from TIMER to ground.

The TIMER pin controls which method of termination the LTC4061 and LTC4062 uses. Connecting an external capacitor to the TIMER pin activates an internal timer that stops the charger after the programmed time period has elapsed. Grounding the TIMER pin and connecting a resistor to the IDET pin causes the charge cycle to terminate once the charge current falls below a programmed threshold (I_{DETECT}). Connecting the TIMER pin to the input supply disables internal termination, allowing the charger to be manually shut down through the enable, $\overline{\text{EN}}$, input.

USB Compatibility

The $\overline{\text{C/5}}$ pin on LTC4061 and LTC4062 provides an easy method to choose between the two different power modes: high power and low power. A logic high on the $\overline{\text{C/5}}$ pin sets the charge current to 100% of the current programmed by the PROG pin resistor (up to 1A), while a logic low on the $\overline{\text{C/5}}$ pin sets the current limit to 20% of the current programmed by the PROG pin resistor. A weak pull down on the $\overline{\text{C/5}}$ pin defaults to the low power state.

The $\overline{\text{C/5}}$ pin provides great flexibility in applications that can automatically choose between wall adapter or USB power, as shown in Figure 1. If wall adapter is present and its voltage is
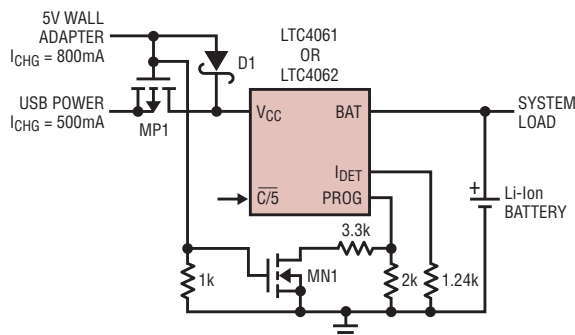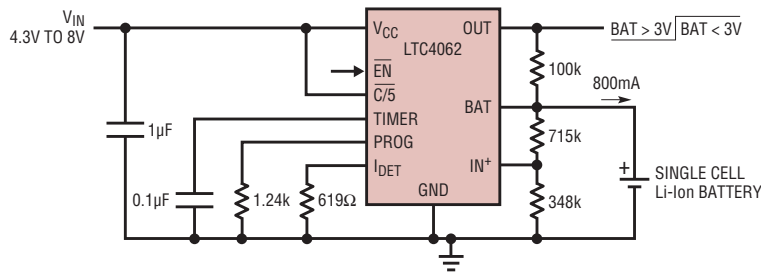
Figure 2. LTC4062 Li-Ion charger configuration using time termination and battery detection

above the V_{TH} of MP1, the power is applied through the diode D1 and the power available through the USB port is not used since MP1 is in open state. MN1 is closed and the 3.3kΩ and 2kΩ resistors are in parallel, setting the total maximum charge current up to 800mA (160mA if $\overline{C/5}$ is set low). If wall adapter is not present, the USB powers the charger; MN1 is open leaving only the 2kΩ resistor to set the charge current up to maximum 500mA. Through the $\overline{C/5}$ pin it is possible to set the charge current to 100mA or 500mA as necessary by USB applications.

Avoiding Unnecessary Charge Cycles

LTC4061 and LTC4062 are designed to avoid unnecessary charge cycles to extend the life of Li-Ion batteries. When power is first applied or when exiting shutdown, the LTC4061 and LTC4062 check the voltage on the BAT pin to determine its initial state. If the BAT pin voltage is below the recharge threshold of 4.1V (which corresponds to approximately 80%–90% battery capacity), the LTC4061 and LTC4062 enter charge mode and begin a full charge cycle. If the BAT pin is above 4.1V, the battery is nearly full and the

charger does not initiate a charge cycle and enters standby mode. When in standby mode, the chargers continuously monitor the BAT pin voltage. When the BAT pin voltage drops below 4.1V, the charge cycle is automatically restarted and the internal timer is reset to half the programmed charge time (if time termination is being used). These features eliminate the need for periodic charge cycle initiations, ensure that the battery is always fully charged and reduce the number of unnecessary charge cycles, prolonging battery life.

Fault Detection and Reporting

LTC4061 has an NTC (Negative Temperature Coefficient) input to qualify charge based on the temperature of the battery, as shown in Figure 3. When the battery temperature is above or below safe levels, charging is suspended, the internal timer is frozen and the $\overline{CHRG}$ pin output blinks with a square wave at either the frequency set with C_{TIMER} (if in timer mode) or 1.5Hz if in current or user termination mode (TIMER connected to GND or to the input supply). The frequency of the blinking using C_{TIMER} is set by the following formula:

$$f_{\overline{CHRG}} = \frac{0.1\mu F}{C_{TIMER}} \bullet 1.5Hz$$

This feature can be disabled by grounding the NTC pin.

While only the LTC4061 has the ability to report a temperature fault, both parts have the ability to report a bad battery. When the BAT pin voltage is below the 2.9V trickle charge threshold (V_{TRIKL}), the charge current is reduced to 10% of the programmed value. If the battery remains in trickle charge for more than 25% of the total programmed charge time, the chargers terminate charging and report that the battery is defective. LTC4061 and LTC4062 report this fault by driving the $\overline{CHRG}$ output with a square wave. The duty cycle of this oscillation is 50% and the frequency is set by C_{TIMER}.

An LED driven by the $\overline{CHRG}$ output exhibits a blinking pattern, indicating to the user that the battery needs replacing. A bad battery fault can be cleared by toggling the $\overline{EN}$ input or removing and reapplying power to V_{CC}. The defective battery detection feature is only available when time termination is being used.

Feature Differences between LTC4061 and LTC4062

In addition to the NTC feature, LTC4061 has an $\overline{ACPR}$ power supply status indicator. When sufficient voltage is present on V_{CC} to charge a battery, this pin is pulled low with an open-drain NMOS device. Otherwise, the pin assumes a high impedance state.

In place of the NTC and $\overline{ACPR}$ functions, the LTC4062 includes an undedicated, precision, low power comparator. The comparator is powered from the BAT pin and consumes just 10µA. The open drain output, OUT, is capable of driving an LED. Possible uses for this comparator include precision low battery detection as shown in Figure 2 and user programmable input supply monitoring.

Conclusion

LTC4061 and 4062 are complete linear Li-Ion battery chargers for wall adapt-
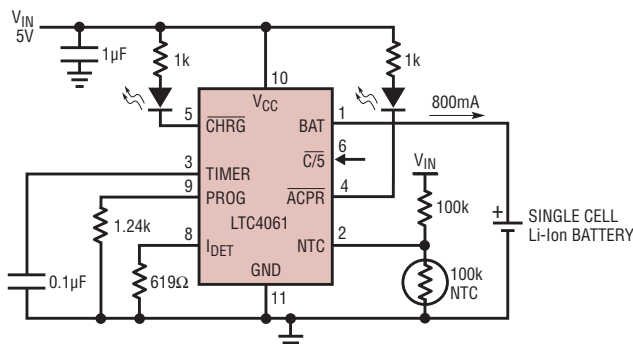
Figure 3. LTC4061 fully featured (using time termination)

Monolithic Buck Regulator Operates Down to 1.6V Input; Simplifies Design of 2-Cell NiCd/NiMH Supplies

by Gregg Castellucci

Introduction

The LTC3409 is a monolithic synchronous step-down regulator designed specifically to save space, improve battery life and simplify the design of 2-cell-alkaline, NiCd and NiMH powered applications. It operates from a wide input voltage range, 1.6 to 5.5V, without the complexity and accompanying loss of efficiency of competing devices that require boost circuitry for generating internal voltages greater than V_{IN}.

Space-saving features include an available 3mm × 3mm DFN package and a high, 1MHz to 3MHz, operating frequency, which allows the use of surface mount capacitors and inductors. To extend battery life, the LTC3409 offers two operating modes that improve light load efficiency, including Burst Mode operation, which consumes only 65µA of supply current at no load, and pulse skipping mode, which offers low ripple currents for noise-sensitive applications. Both modes consume less than 1µA quiescent current in shutdown.

The LTC3409 also features soft start, which limits inrush current at start-up.

Features

Soft Start

To reduce inrush currents at start-up, the LTC3409 offers a soft start function, which linearly ramps up the output voltage in about 1ms. For instance, the average output current required during soft start to charge a 10µF output capacitor to 1.8V in 1ms is 18mA. The total output current is the sum of the output capacitor charging current and the current delivered to the load as V_{OUT} ramps up.
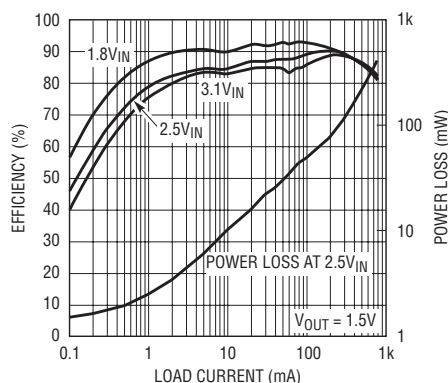

Figure 1. Efficiency vs load current for the LTC3409 in Burst Mode operation.
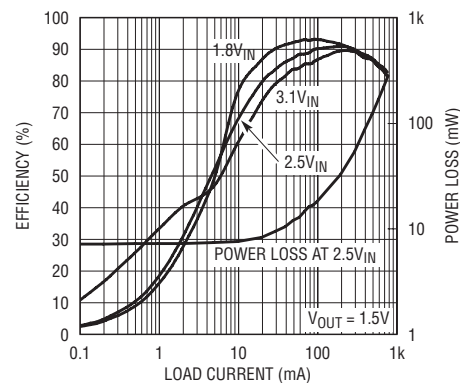

Figure 2. Efficiency vs load current for the LTC3409 in pulse skip mode.

Switching Frequency Synchronization

The LTC3409 offers an internally compensated phase locked loop (PLL) for switching frequency synchronization from 1MHz to 3MHz in addition to fixed frequencies of 1.7MHz and 2.6MHz. This high frequency range allows the use of surface mount capacitors and inductors.

The sync pin has three states: high, where the LTC3409 operates at a fixed 2.6MHz switching frequency; low, where the LTC3409 operates at a fixed 1.7MHz switching frequency; or as the input to the PLL, when the sync pin is toggled at a frequency of at least 1MHz for greater than 100µs. The SYNC pin threshold for PLL input is nominally

0.63V, thus allowing compatibility to low voltage logic interfaces.

Efficiency-Improving Operating Modes

The Mode pin has two states corresponding to two operating modes that improve efficiency at light loads: high for pulse skip mode, and low for Burst Mode operation. In pulse skipping mode, constant-frequency operation is maintained at lower load currents to decrease the output voltage ripple, and therefore reduce the chance of interference with audio circuitry. If the load current is low enough, cycle skipping eventually occurs to maintain regulation. Efficiency in pulse skipping mode is worse than Burst Mode op-
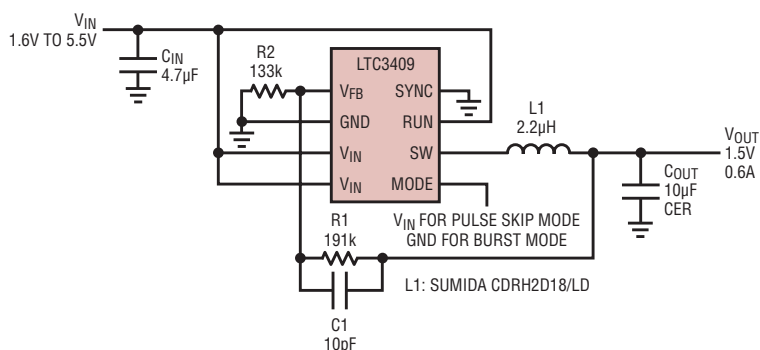

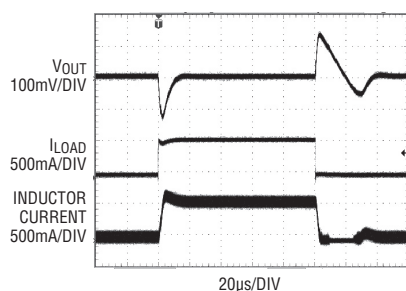Figure 3. 1.5V/600mA step down regulator

Figure 4. LTC3409 transient response to a 50mA–600mA load step, pulse skip mode

eration at light loads, but comparable when the output load exceeds 50mA (see Figure 1 & 2).

In Burst Mode operation, the internal power MOSFETs operate intermittently based on load demand. Short burst cycles of normal switching are followed by longer idle periods where the load current is supplied by the output capacitor. During the idle period, the power MOSFETs and any unneeded circuitry are turned off, reducing the quiescent current to 65µA. At no load, the output capacitor discharges slowly through the feedback resistors resulting in very low frequency burst cycles that add only a few µA to the supply current. Burst Mode operation offers higher efficiency at low output currents than pulse skip mode, but when activated, Burst Mode operation produces higher output ripple than pulse skip mode.

Output Voltage Programmability

The LTC3409 output voltage is externally programmed with two resistors to any value above the 0.613V internal reference voltage, and is capable of 100% duty cycle. In dropout, the output voltage is determined by the input voltage minus the voltage drop

across the internal P-channel MOSFET and the inductor resistance.

Fault Protection

The LTC3409 protects against output over-voltage, output short-circuit and power over-dissipation conditions. When an over-voltage condition at the output (>10% above nominal) is sensed, the top MOSFET is turned off until the fault is removed. If the output is shorted to ground, reverse current in the synchronous switch is monitored to prevent inductor-current runaway. If the synchronous switch current is too high, the top MOSFET remains off until the synchronous switch current falls to a normal level.

When the junction temperature reaches approximately 160°C, the thermal protection circuit turns off the power MOSFETs allowing the part to cool. Normal operation resumes when the die temperature drops to 150°C.

1.5V/600mA Step-Down Regulator Using Ceramic Capacitors

Figure 3 shows an application of the LTC3409 using ceramic capacitors. This particular design supplies up to a 600mA load at 1.5V with an input supply between 1.8V and 3.1V. Ceramic capacitors have the advantages of small size and low equivalent series resistance (ESR), allowing very low ripple voltages at both the input and output. Because the LTC3409's control loop does not depend on the output capacitor's ESR for stable operation, ceramic capacitors can be used to achieve very low output ripple and small circuit size. Figures 4 and 5 show the transient response to a 50mA
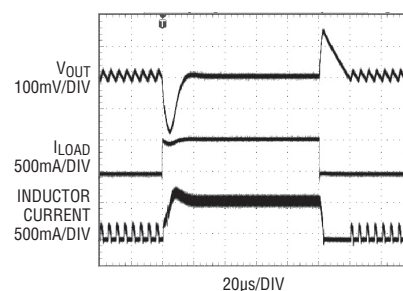

Figure 5. LTC3409 Transient response to a 50mA–600mA load step, Burst Mode operation

to 600mA load step for the LTC3409 in pulse skip mode, and burst mode.

Efficiency Considerations

Figure 1 shows the efficiency curves for the LTC3409 (Burst Mode operation enabled) at various supply voltages. Burst Mode operation significantly lowers the quiescent current, resulting in high efficiencies even with extremely light loads. Figure 2 shows the efficiency curves for the LTC3409 (pulse skipping mode enabled) at various supply voltages. Pulse skipping mode maintains constant-frequency operation at lower load currents. This necessarily increases the gate charge losses and switching losses, which impact efficiency at light loads. Efficiency is still comparable to Burst Mode operation at higher loads.

Conclusion

The LTC3409 operates over a wide, 1.6V to 5.5V, input range, which allows it to operate from various power sources, from a 5V AC wall adapter to two series alkaline batteries. This flexible device is available in a 3mm × 3mm DFN package and includes a number of features to improve battery life and save space. ⌐⌐

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ers and USB sources. They extend lifetime of the batteries by avoiding unnecessary charge cycles. The LTC4061 and LTC4062's versatility of charge

terminations, low quiescent current, simplicity, high level of integration and small size makes them an ideal choice for many portable USB applications.

LTC4061 and LTC4062 are available in a small 10-lead low profile 3mm x 3mm DFN package. ⌐⌐

Supply Tracking and Sequencing at Point-of-Load: Easy Design without the Drawbacks of MOSFETs

by Scott Jackson

Introduction

Multi-voltage electronics systems are often saddled with complex power supply voltage tracking or sequencing requirements, which, if not met, can result in system faults or even permanent failures in the field. The design difficulties in meeting these requirements are often compounded in distributed-power architectures where point-of-load (POL) DC/DC converters are scattered across PC board space, sometimes on different board planes. The problem is that power supply circuitry is often the last circuitry to be designed into the board, and it must be shoehorned into whatever little board real estate is left. Centralized sequencing-tracking solutions can work well, but when no significant contiguous space is left on a board and the system specifications are in flux, one wishes for a simple, drop-in, flexible option. That wish can be fulfilled with a tracking and sequencing solution that installs at the POL, and is tiny and versatile enough to be easily dropped into the board without disrupting the rest of the system design.

Wish Granted

The LTC2927 provides a simple and versatile solution in a tiny footprint for both tracking and sequencing without the drawbacks of series MOSFETs.

Each POL converter that must be tracked or sequenced can have a single LTC2927 placed at point-of-load as shown in Figure 1. By selecting a few resistors and a capacitor, the supplies are configured to ramp-up and ramp-down with a variety of voltage profiles. Figure 2 shows various tracking and sequencing scenarios, including concurrent voltage tracking (Figure 2a), offset tracking (Figure 2b), ratiometric tracking (Figure 2c), and supply sequencing (Figure 2d).

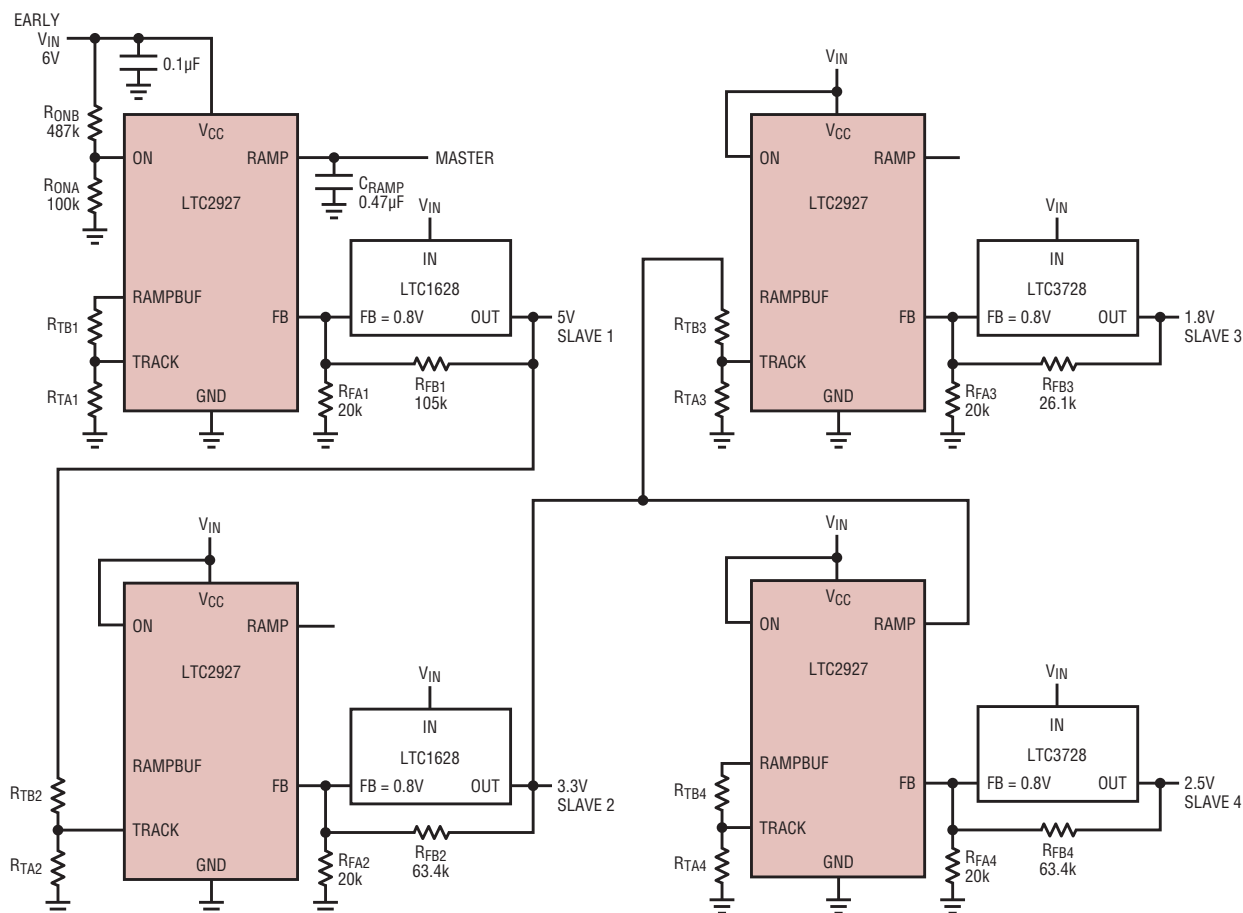Many voltage tracking solutions use series MOSFETs, which adds an in-

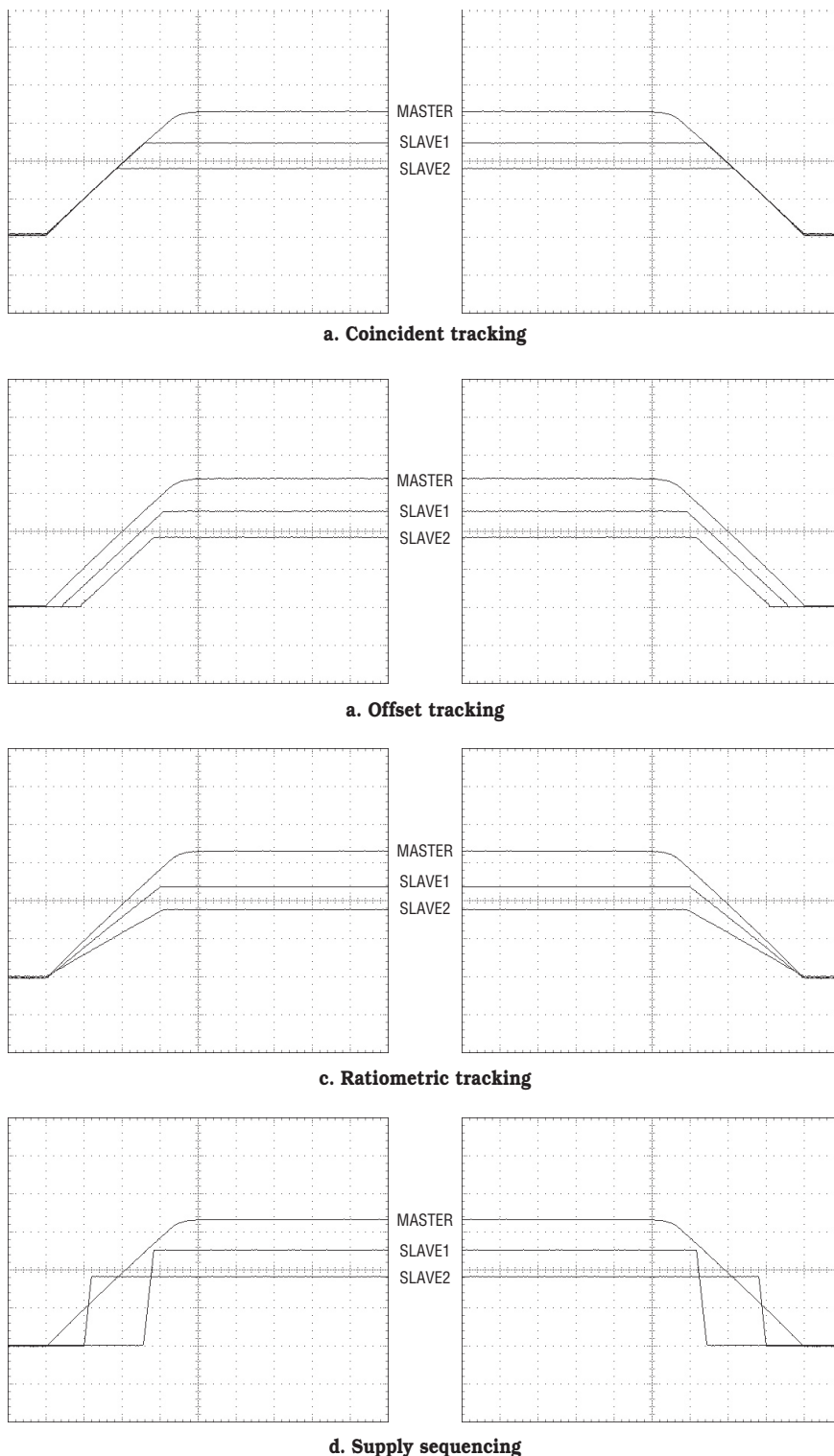**Figure 1. Typical tracking application**

a. Coincident tracking

a. Offset tracking

c. Ratiometric tracking

d. Supply sequencing

Figure 2. Types of power supply voltage tracking

herent voltage drop, additional power consumption, and extra PC board real estate. Instead, the LTC2927 controls supplies by injecting current directly into the feedback nodes, thus controlling supply outputs without series MOSFETs. Figure 3 shows the simple "tracking cell" used to inject this current. *Furthermore, power supply stability and transient response remain unaffected because the injected current from the LTC2927 offsets the output voltage without altering the power supply control loop dynamics.*

Power supply tracking is straightforward with the LTC2927. A pair of resistors configures the behavior of a slave supply relative to a master signal. The choice of resistors can cause a slave supply to track the master signal exactly or with a different ramp rate, voltage offset, time delay, or combination of these.

A master signal is generated by tying a capacitor from the RAMP pin to ground or by supplying another ramping signal to be tracked as shown in Figure 1.

Examples

Consider a complex tracking system. The schematic in Figure 1 uses an LTC1628 dual synchronous step-down converter to produce 5.0V and 3.3V supplies and an LTC3728 dual synchronous step-down converter to produce 2.5V and 1.8V supplies from a 6.0V input. Four LTC2927s connected to the feedback nodes control the ramp-up and ramp-down behavior of these supplies. An early V_{IN} is supplied to the devices to guarantee correct operation prior to tracking the supplies.

The specification calls for the 5.0V and 3.3V supplies to track coincidently at ~20V/s, the 1.8V supply should ramp up quickly at 100V/s after the 3.3V supply reaches 2.0V, and the 2.5V supply should ramp up at the same rate as the 1.8V supply, but delayed by 20ms. The LTC2927 data sheet (available at www.linear.com) includes a 3-step design procedure that is followed for each supply. When using that procedure, use the following for equation (1) in Step 1, with a master signal ramp-rate S_M of 20V/s:

$$C_{RAMP} = \frac{10\mu A}{20\,V/s} \approx 0.47\mu$$

5V and 3.3V Supply Coincident Tracking

Because the master ramp rate is chosen to be equal to the desired ramp rate of the 5V and 3.3V supplies, coincident tracking is selected. If the feedback voltage of the switching power supply is 0.8V, as it is on the LTC1628, then coincident tracking can be configured by setting the tracking resistors equal to the feedback resistors (verified by

Figure 3. Simplified tracking cell

Figure 4. Output profile of the circuit in Figure 1

following Step 2 of the 3-Step Design Procedure),

From equation (2) of the 3-Step Design Procedure:

$R_{TB1} = R_{FB1} = 105\text{k}\Omega$
$R_{TB2} = R_{FB2} = 63.4\text{k}\Omega$

From Equation (3) of the 3-Step Design Procedure:

$R_{TA1}' = R_{FA1} = 20\text{k}\Omega$
$R_{TA2}' = R_{FA2} = 20\text{k}\Omega$

In the 3-step design procedure R_{TA}' represents the value of R_{TA} that produces no delay or offset. Since no delay is desired, $R_{TA} = R_{TA}'$, and Step 3 of the Design procedure is unnecessary.

1.8V and 2.5V Supply Sequencing

The 1.8V supply ramps up 2V below the 3.3V supply but at a ramp rate of 100V/s. Set the slave ramp rate to 100V/s in equation (2) to find R_{TB3}:

$$R_{TB3} = 26.1\text{k}\Omega\frac{21.3\,\text{V/s}}{100\,\text{V/s}} \approx 56.2\text{k}\Omega$$

Complete Step 2 by solving for R_{TA3}' using equation (3).

$$R_{TA3}' = -10.755\text{k}\Omega$$

Step 3 adjusts R_{TA3} for the desired delay between the 3.3V supply and the 1.8V supply. An offset of 2V results in a delay of ~100ms for the ramp rate chosen.

$$R_{TA3}'' = 2.09\text{k}\Omega$$

$$R_{TA3} = R_{TA3}' \parallel R_{TA3}''$$
$$\approx 2.61\text{k}\Omega$$

The 2.5V supply has the same ramp rate as the 1.8V supply, but

is delayed another 20ms. Repeating Step 2 and Step 3 for the 2.5V supply results in:

$$R_{TB4} = 43.2\text{k}\Omega\frac{21.3\,\text{V/s}}{100\,\text{V/s}} \approx 93.1\text{k}\Omega$$

$$R_{TA4}' = -28.052\text{k}\Omega$$

$$R_{TA4}'' = 28.8\text{k}\Omega$$

$$R_{TA4} = R_{TA4}' \parallel R_{TA4}''$$
$$\approx 3.24\text{k}\Omega$$

The tracking profile for this system is shown in Figure 4.

Note that not every combination of ramp-rates and delays is possible. Small delays and large ratios of slave ramp rate to master ramp rate may result in solutions that require negative resistors. In such cases, either the delay must be increased or the ratio of slave ramp rate to the master ramp rate must be reduced. In addition, the chosen resistor values should not require more than 1mA to flow from

the TRACK and FB pins. Therefore, confirm that less than 1mA flows from TRACK when V_{MASTER} is at 0V.

$$I_{TRACK1} = \frac{V_{TRACK}}{R_{TA1} \parallel R_{TB1}}$$
$$= 0.05\text{mA} < 1\text{mA}$$

$$I_{TRACK2} = \frac{V_{TRACK}}{R_{TA2} \parallel R_{TB2}}$$
$$= 0.05\text{mA} < 1\text{mA}$$

$$I_{TRACK3} = \frac{V_{TRACK}}{R_{TA3} \parallel R_{TB3}}$$
$$= 0.45\text{mA} < 1\text{mA}$$

$$I_{TRACK4} = \frac{V_{TRACK}}{R_{TA4} \parallel R_{TB4}}$$
$$= 0.24\text{mA} < 1\text{mA}$$

The connections between each LTC2927 shown in Figure 1 allow extra control for each supply. With this system, the 3.3V supply uses the 5V supply as its master signal. If for some reason the 5V supply should collapse, the 3.3V supply follows it down. Likewise, the 1.8V and 2.5V supplies use the 3.3V supply as their master signal and track it up and down.
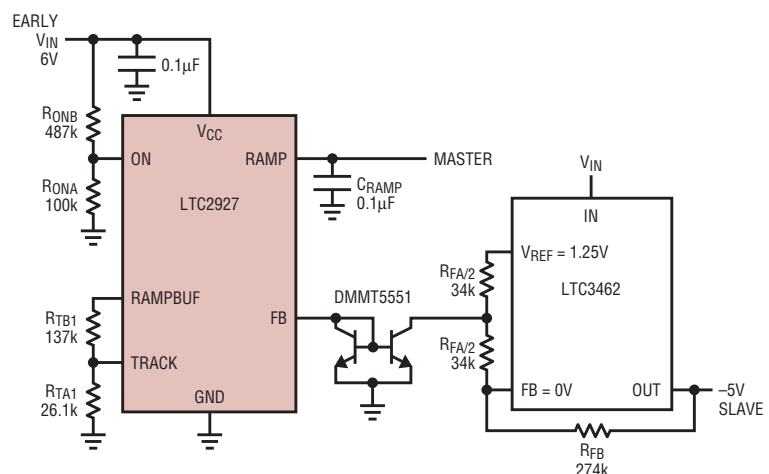

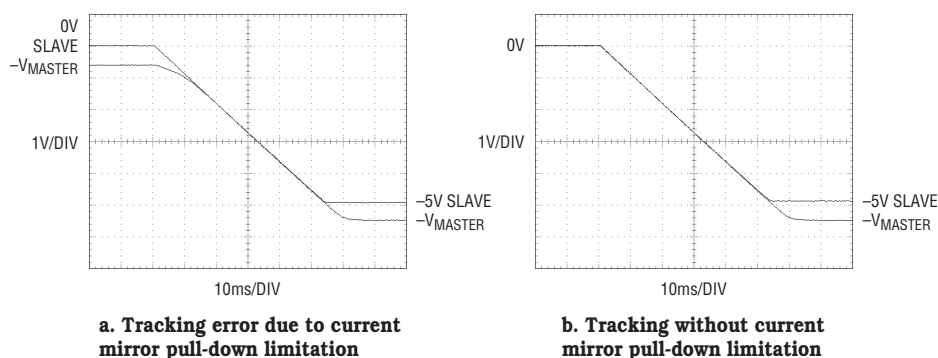Figure 5. Supply tracking of GND referenced negative regulator

a. Tracking error due to current mirror pull-down limitation

b. Tracking without current mirror pull-down limitation

Figure 6. Output profile of circuit of Figure 9

Negative Supply Tracking

It is possible to track negative voltage regulators with the LTC2927. Figure 5 shows a tracking example using a LT3462 inverting DC/DC converter to produce a –5V supply. This converter has a ground-based reference, which allows current to be pulled from a node where R_{FA} has been divided in two. To properly pull current from the LT3462 FB network, a current mirror must be placed between the LTC2927 and the converter. The 3-Step design procedure remains the same with minor modifications to equations (2) and (3):

$$R_{TB} = \frac{R_{FB}}{2} \bullet \frac{S_M}{S_S}$$

$$R_{TA}' = \frac{V_{TRACK}}{\dfrac{2V_{REF}}{R_{FA}} - \dfrac{V_{TRACK}}{R_{TB}}}$$

All other equations remain the same.

Figure 6a shows the tracking profile of Figure 5 with a ramp rate of 100V/s. V_{MASTER} is positive, but the inverse is shown for clarity. The –5V slave does not pull all the way up to 0V at V_{MASTER} = 0V. This is because the ground referenced current mirror cannot pull its output all the way to ground. If the converter has a FB reference voltage greater than 0V or if a negative supply is available for the current mirror, the error can be removed. The resulting waveform is shown in Figure 6b.

Conclusion

The LTC2927 simplifies power supply tracking and sequencing by offering superior performance in a tiny point-of-load area. A few resistors can configure simple or complex supply behaviors. Series MOSFETs are eliminated along with their parasitic voltage drops and power consumption. The LTC2927 offers all of these features in a tiny 8-lead ThinSOT™ and 8-lead (3mm × 2mm) DFN package. *LT*

ESR generates a loop zero at 5kHz to 50kHz that is instrumental in giving acceptable loop phase margin. Ceramic capacitors remain capacitive to beyond 300kHz and usually resonate with their ESL before ESR becomes effective. Also, ceramic caps are prone to temperature effects, requiring the designer to check loop stability over the operating temperature range. For these reasons, great care must be taken when using only ceramic input and output capacitors. The LTC3417 helps solve loop stability problems with its OPTI-LOOP phase compensation adjustment, allowing the use of ceramic capacitors. For details, and a process for optimizing compensation components, see Linear Technology Application Note 74 (AN76).

Although the LTC3417 is capable of operating at 4MHz, the frequency in this application is set for 1.5MHz by connecting the FREQ pin to V_{IN}.

Figures 5 through 7 show the trade off between mode and V_{OUT} ripple noise. Figure 5 shows the voltage ripple at V_{OUT1} and the current through the inductor while the LTC3417 is in Burst Mode operation. The ripple voltage in this example was taken at an I_{LOAD} of 40mA and is only 15m$V_{P–P}$. The worst case output voltage ripple occurs just before the part switches from bursting to continuous mode, which occurs at about 250mA. At his point, the V_{OUT} ripple can be as high as 25m$V_{P–P}$.

Figure 6 shows the V_{OUT1} ripple and the current through the inductor when the part is in Pulse Skipping Mode. Notice that the current through the inductor does go slightly negative, and then produces some high frequency components. The higher frequency components are due to the switching MOSFETS turning off. At lower currents, the part starts skipping pulses, and thus produces some lower frequency components. In this case, the voltage ripple does indeed show some higher frequency components, yet the ripple itself is at about 5m$V_{P–P}$.

Figure 7 shows the voltage ripple at V_{OUT1} and the inductor current when the part is in Forced Continuous mode. Notice that the current through the inductor goes negative. At no time, during Forced Continuous doe the MOSFETS actually turn off, they keep switching. Therefore, the frequency component of the voltage ripple stays constant at the operating frequency. The voltage ripple therefore looks constant and stays below 5mV over all load currents.

Conclusion

The LTC3417 is a dual synchronous, step-down, current mode, DC/DC converter designed to fit in the tight spaces afforded by today's portable devices. Switching MOSFETS are integrated into the device, and high frequency operation enables the use of small sized components. It is also designed with versatility in mind with external components for loop compensation, variable frequency operation and different operating modes to optimize efficiency and noise. *LT*

Versatile Controller Simplifies High Voltage DC/DC Converter Designs

by Tom Sheehan

Introduction

The LT3724 is a single-switch DC/DC controller that can be used in medium power step-down, step-up, inverting and SEPIC converter topologies. It offers simple solutions to regulating system voltages at high efficiencies over a wide input voltage range (4V–60V) and wide load range.

LT3724 Features

The LT3724 uses a 200kHz fixed-frequency current-mode architecture. An internal high voltage bias regulator allows for simple startup and biasing, and it can be back driven by the output to increase supply efficiency and lower power dissipation in the IC.

User selectable Burst Mode operation can maintain high efficiency over a wide load range. In Burst Mode operation quiescent current is reduced to under 100µA, making the LT3724 ideal for use in applications with supply maintenance requirements or light load and no-load conditions. A precision shutdown pin threshold allows for easy supply under voltage lockout where quiescent currents are reduced to less than 10µA.

Supply short circuit control is via an external sense resistor, through which the LT3724 continuously monitors inductor current. If the inductor current
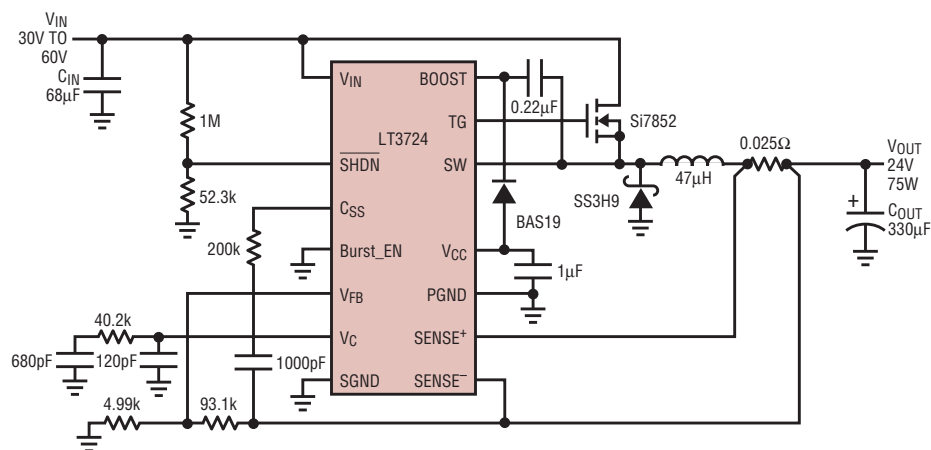

Figure 1. 30V–60V to 24V 75W DC/DC converter with input UVLO and full time usage of on board high voltage regulator

exceeds the maximum current sense threshold, pulse skipping occurs.

The LT3724 also incorporates a programmable soft-start that controls the slew rate of the converter output voltage during startup to reduce supply inrush currents and output voltage overshoot.

The gate driver is capable of driving large, low $R_{DS(ON)}$, standard level, n-channel MOSFETS without the need for a gate drive buffer. The driver uses a bootstrapped supply rail which allows it to drive either a high side MOSFET, as found in buck converters, or a low side MOSFET, as found in boost converters.

On-Board Regulator

The LT3724's internal 8V linear regulator eliminates the need for an external regulator or a slow-charge hysteretic start scheme. This regulator generates the local supply that powers the IC (V_{CC}), from the converter input supply, V_{IN}.

The on-board regulator can operate the IC continuously, provided the input voltage and/or FET gate charge currents are low enough to avoid excessive power dissipation in the part.

Common practice uses the on board regulator during startup and then back drives the V_{CC} pin above its 8V regulated voltage during operation. This reduces the power dissipation in the IC and increases converter efficiency. The LT3724 has a start-up requirement of $V_{IN} \geq 7.5V$. This assures that the on-board regulator brings the V_{CC} pin above its undervoltage lockout threshold of 6.25V. If V_{CC} is maintained using an external supply, such as the converter output, the LT3724 can continue to operate with V_{IN} as low as 4V.

Burst Mode Operation

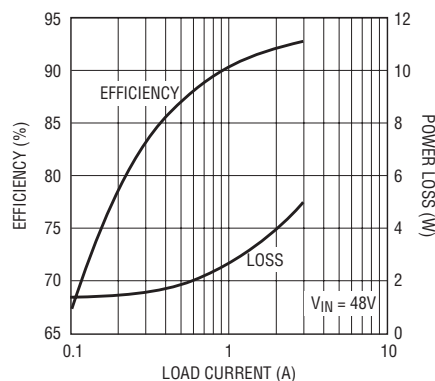The LT3724 employs low-current Burst Mode operation to maximize ef-

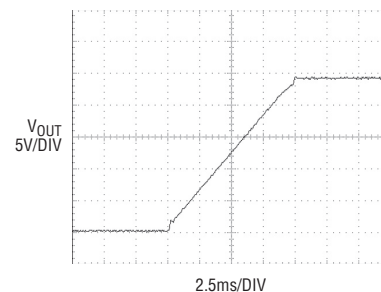Figure 2. 30V–60V to 24V, 75W DC/DC converter efficiency and power loss

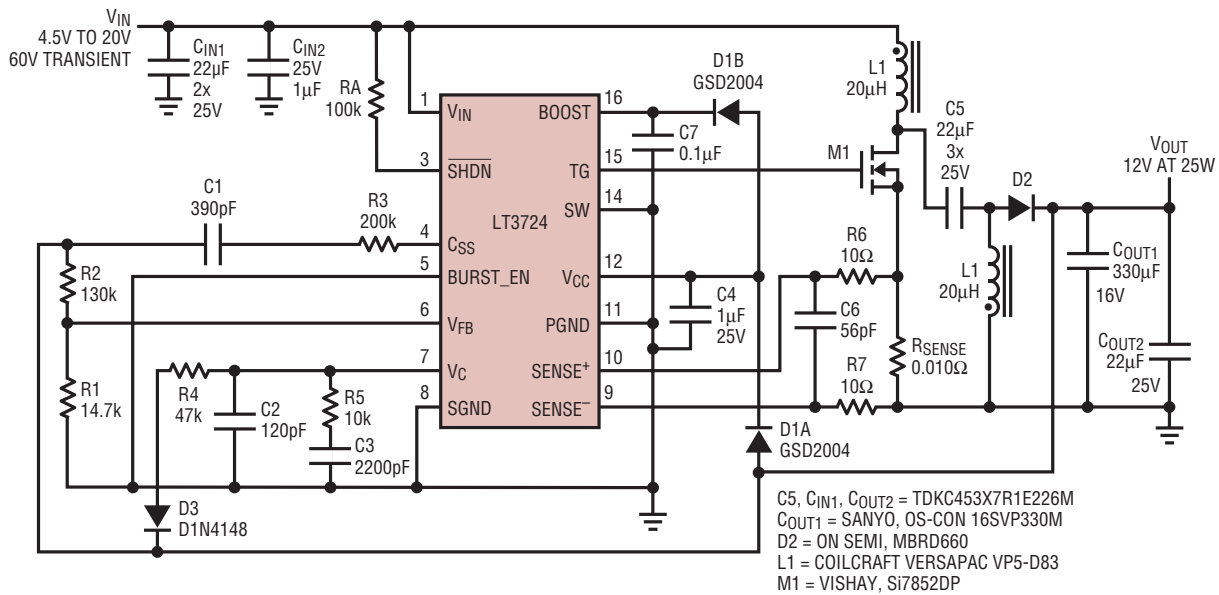Figure 3. 30V–60V to 24V, 75W DC/DC converter output soft-start waveform

Figure 4. 15V to 12V 25W SEPIC DC/DC converter

ficiency during light-load and no-load conditions. Burst Mode is enabled by shorting the BURST_EN pin to SGND and can be disabled by shorting BURST_EN to V_{FB}.

When the required switch current, sensed via the V_C pin voltage, is below 15% of programmed current limit, the Burst Mode function is engaged. During the Burst interval, switching ceases and all internal IC functions are disabled, with the exception of the V_{CC} regulator, error amplifier, and bandgap reference. Current at the V_{IN} pin is reduced to 20µA and V_{CC} current is reduced to 80µA. If no external

drive is provided for V_{CC}, all V_{CC} bias currents originate from the V_{IN} pin, giving a total V_{IN} current of 100µA. An internal negative-excursion clamp on the V_C pin is set at 100mV below the switch disable threshold, limiting the negative excursion of the pin voltage and minimizing converter output ripple during Burst Mode operation.

Precision Shutdown Threshold

The LT3724 $\overline{SHDN}$ pin is used for precision shutdown in analog monitoring applications, as well as logic-level controlled applications. Input supply undervoltage lockout for supply
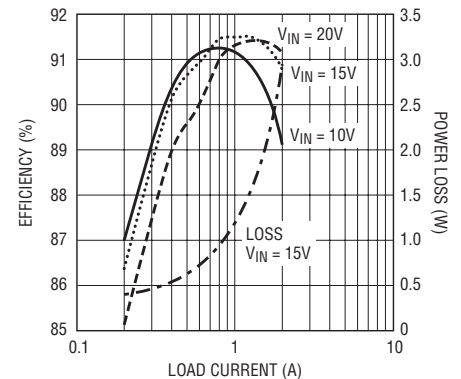

Figure 5. 15V to 12V 25W SEPIC DC/DC converter efficiency and power loss

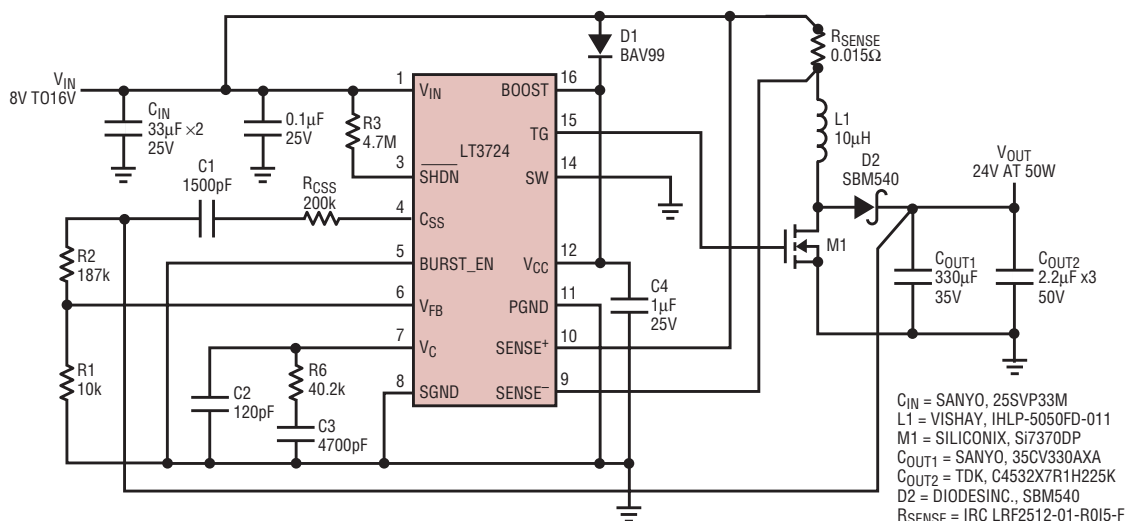sequencing or start-up over-current protection is easily achieved by driving

Figure 6. 12V to 24V/50W boost converter

the $\overline{\text{SHDN}}$ pin with a resistor divider from the V_{IN} supply, such that the divider output is 1.35V when V_{IN} is at the desired undervoltage lockout rising threshold voltage. 120mV of input hysteresis on the $\overline{\text{SHDN}}$ pin allows the IC to withstand almost 10% of input supply droop before disabling the converter. The $\overline{\text{SHDN}}$ pin has a secondary threshold of 0.5V, below which the IC operates in an ultra-low-current shutdown mode with I_{VIN} < 10 μA. The shutdown function can be disabled by connecting the $\overline{\text{SHDN}}$ pin to V_{IN} through a large value pull-up resistor.

Continuous High-Side Inductor Current Sensing

The LT3724 uses a wide common-mode input range current sense amplifier that operates over a 0V to 36V range. This current sense amplifier provides continuous inductor current sensing via an external sense resistor. This scheme does not require blanking intervals or a minimum on-time to monitor current, an advantage over schemes that sense switch current. The sense amplifier monitors inductor current independent of switch state, so the main switch is not enabled unless the inductor current is below the current that corresponds to the V_C pin voltage. This "turn-on" decision is performed at the start of each cycle, and individual switch cycles are skipped should an over-current condition occur. This eliminates many of the potential over-current dangers caused by minimum on-time requirements, such as those that can occur during startup, short-circuit, or abrupt input transients.

Current Mode Control

The LT3724 uses current mode control architecture enabling a higher supply bandwidth thereby improving line and load transient response. Current mode control also requires fewer compensation components than voltage mode control architectures, making it much easier to compensate over all operating conditions.
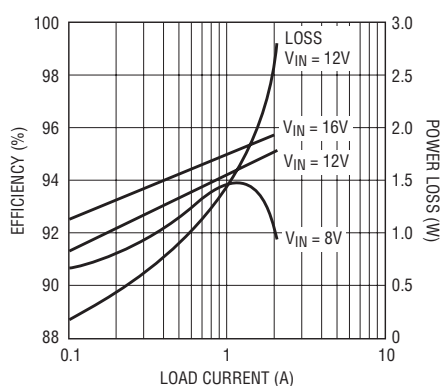

Figure 7. 12V to 24V/50W boost converter efficiency and power loss

Soft Start

The LT3724 employs an adaptive soft-start scheme that directly controls the rising rate of DC/DC converter output voltage. Output voltage overshoot and inrush current are well controlled with this method. This rising rate of the output voltage is programmed with a capacitor connected to the converter output, where:

$$2\mu A = C_{OUT} \cdot (\text{Desired } \Delta V / \Delta t)$$

The soft-start function maintains this desired output rising rate up to 95% of the regulated output voltage. The soft-start function is re-enabled if the converter output droops below 70% regulation, so converter recovery is graceful from a short-duration shutdown or an output short-circuit condition.

Applications

The applications here present only a small sample of what can be accomplished with the LT3724. See the data sheet at www.linear.com for more, including an inverting converter.

30V–60V to 24V, 75W DC/DC Converter

Figure 1 shows a 30V–60V to 24V, 75W converter configured for supply input undervoltage lockout and full time usage of the onboard high voltage bias regulator. This application demonstrates how a high efficiency supply can be built inexpensively and with fewer than 20 components. Figure 2 shows the converter efficiency and power loss vs load current.

Power for the IC is obtained directly from V_{IN} through the LT3724's internal V_{CC} regulator. V_{IN} UVLO is programmed via a resistor divider to enable the LT3724 at 90% of the specified low end of V_{IN} range, or 27V, which corresponds to the $\overline{\text{SHDN}}$ pin voltage exceeding 1.35V. The $\overline{\text{SHDN}}$ input has 120mV of hysteresis, so the converter is disabled if V_{IN} drops below 24V.

The LT3724 soft-start function controls the rising slew rate of the output voltage at startup such that the current through the soft start capacitor is 2μA, so the converter output rises at a controlled rate of 2μA/1nF, or 2V/mS. Figure 3 shows the soft start ramp.

4V–60V to 12V, 2A SEPIC Converter

In LT3724 converter applications with output voltages in the 9V to 20V range, back-feeding V_{CC} from the converter output is accomplished by connecting a diode from the supply output to the V_{CC} pin. Figure 4 shows a 15V to 12V, 2A SEPIC converter configured to use the 12V output voltage to back drive V_{CC}. This application also shows the versatility of the LT3724 by configuring it to control a SEPIC converter. SEPIC converters are used where the input voltage can be both less than or greater than the output voltage, such as a battery powered application.

In some DC/DC converter applications, the converter must withstand or operate through intermittent input voltage excursions. This is typical of automotive battery-voltage applications, where high voltage line transients such as load-dump or low voltage transients such as startup must be accommodated. This converter design is optimized to operate with a 15V nominal input voltage but can regulate the output voltage over a wide input range of 4V to 60V. Figure 5 shows the converter efficiency and power loss vs load current.

This converter also uses an external current limit fold-back scheme. This fold-back circuit consists of a single 1N4148 diode (D2) and a resistor (R5).

Multichannel, 3V and 5V, 16-Bit ADCs Combine High Performance, Speed, Low Power and Small Size

by Ringo Lee

Introduction

Many of today's data acquisition applications require low-power and/or remote sensing capabilities while occupying a minimum amount of board space. Linear Technology introduces a pin-compatible family of 12-bit and 16-bit A/D converters that meet these requirements. The flagship device of this new family is the LTC1867. It consists of an 8-channel analog input multiplexer (MUX), a high performance and lower-power 16-bit switched capacitor A/D converter, a simple serial I/O, and fits in a small 16-pin narrow SSOP package (5mm × 6mm footprint).

Product Features

❑ Sample Rate: 200ksps (LTC1867); 175ksps (LTC1867L)
❑ 16-Bit No Missing Codes
❑ 8 Single-Ended or 4 Differential Channels
❑ SPI/MICROWIRE™ Serial I/O
❑ On-Board or External Reference
❑ Low Power Operation: 1.3mA (LTC1867); 0.75mA (LTC1867L)
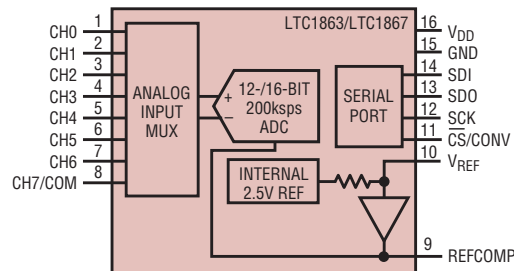❑ Automatic Nap and Sleep Modes
❑ 16-Pin Narrow SSOP Package

Figure 1. The simplified block diagram of the LTC1863 and LTC1867, which include a programmable 8-channel input multiplexer, 16-bit switched capacitor ADC and an on-board reference.

Table 1 identifies the differences between the four members of this new family of high performance A/D converters. The members are classified according to supply voltage and resolution. The 16-bit LTC1867 and the 12-bit LTC1863 operate on a single 5V supply while sampling at 200ksps. The LTC1867L and the LTC1863L operate on a reduced 3V supply with the same features of the LTC1867 and the LTC1863, respectively. The LTC1867L and LTC1863L key specifications are guaranteed for 2.7V operation. In addition, all four parts provide an automatic Nap mode, Sleep mode, unipolar and bipolar operation, and an internal bandgap reference. Figure 1 shows a block diagram for the LTC1867/LTC1863.

MUX Configuration

The eight-channel analog input multiplexer can be selected either in 4 differential pairs, 8 single-ended, 7 single-ended channels versus COMMON pin (pin 8, CH7/COM acts as COMMON MINUS) or combinations thereof. These configurations are set up by a 7-bit input word defined in Table 2 through the SDI/SCK serial port. The channel-to-channel matching for offset and gain error are excellent. For the LTC1867, the offset error match and gain error match are both specified as ±2LSB (max). The crosstalk between channels is typically better than 110dB. Figure 2 illustrates the flexibility of the 8-channel MUX.

Unipolar and Bipolar Mode

These A/D converters can sample the difference of positive input ($+V_{IN}$) and negative input ($-V_{IN}$) at the same instant either in unipolar or bipolar modes depending on UNI bit of the Input Word. For the LTC1867 and LTC1863, the input ranges (i.e. $+V_{IN}$ minus $-V_{IN}$) are 0V to 4V in unipolar mode and ±2V in bipolar mode. For example, the $+V_{IN}$ can swing from 0V to 4V if $-V_{IN}$ is tied to Ground in unipolar mode, and the $+V_{IN}$ can swing from

Table 1. LTC1867 Family Members

Part Number	LTC1867	LTC1863	LTC1867L	LTC1863L
V_{DD}	5V	5V	3V	3V
Resolution	16-Bit	12-Bit	16-Bit	12-Bit
f_{SAMPLE}	200ksps	200ksps	175ksps	175ksps
Input Ranges	0V–4V, ±2V	0V–4V, ±2V	0V–2.5V, ±1.25V	0V–2.5V, ±1.25V
Supply Current	1.3mA	1.3mA	0.75mA	0.75mA
INL (Unipolar)	±2LSB	±1LSB	±3LSB	±1LSB
INL (Bipolar)	±2.5LSB	±1LSB	±3LSB	±1LSB
No Missing Codes	YES	YES	YES	YES

4 Differential

```
+ (−)⎰ CH0
− (+)⎱ CH1

+ (−)⎰ CH2
− (+)⎱ CH3

+ (−)⎰ CH4
− (+)⎱ CH5

+ (−)⎰ CH6
− (+)⎱ CH7/COM
```

8 Single-Ended

```
+ ── CH0
+ ── CH1
+ ── CH2
+ ── CH3
+ ── CH4
+ ── CH5
+ ── CH6
+ ── CH7/COM

    GND (−)
```

7 Single-Ended to CH7/COM

```
+ ── CH0
+ ── CH1
+ ── CH2
+ ── CH3
+ ── CH4
+ ── CH5
+ ── CH6

    CH7/COM (−)
```

Combinations of Differential and Single-Ended

```
+ ⎰ CH0
− ⎱ CH1

− ⎰ CH2
+ ⎱ CH3

+ ── CH4
+ ── CH5
+ ── CH6
+ ── CH7/COM

    GND (−)
```

1st Conversion

```
+ ⎰ CH2
− ⎱ CH3

+ ⎰ CH4
− ⎱ CH5

    CH7/COM
    (UNUSED)
```

2nd Conversion

```
− ⎰ CH2
+ ⎱ CH3

+ ⎰ CH4
+ ⎱ CH5

    CH7/COM (−)
```
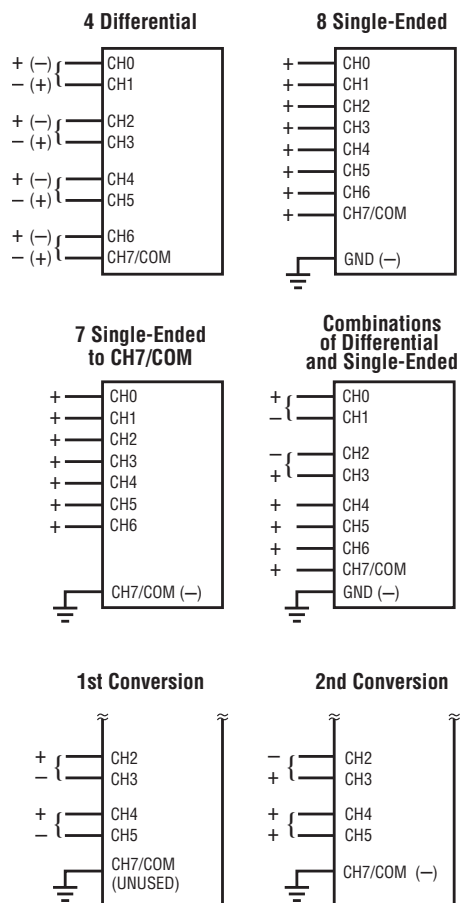
Figure 2. These examples show the flexibility of the LTC1867 8-channel input multiplexer.
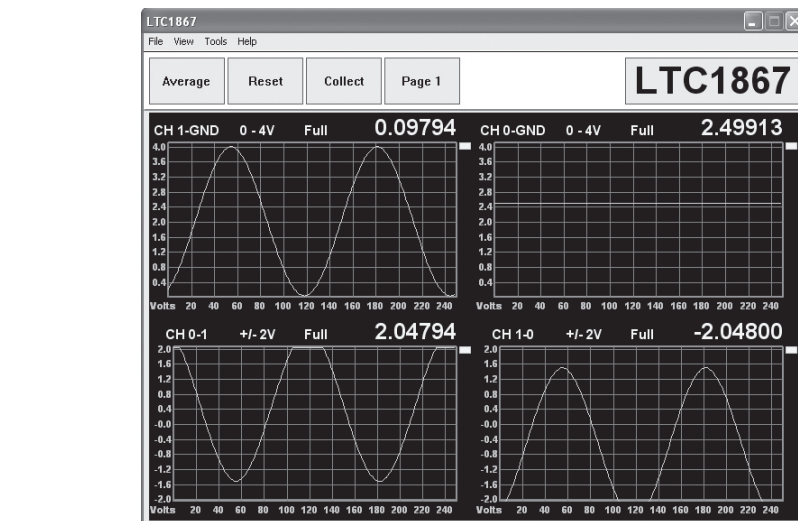

Figure 3. The upper two traces show the digitized results from the LTC1867 operating in the unipolar mode with signals applied to Channel 1 and Channel 0. The lower traces demonstrate how the results are changed when LTC1867 is configured to operate in the bipolar mode with the same signals applied to Channel 1 and Channel 0.

0.5V to 4.5V if $-V_{IN}$ is tied to 2.5V in bipolar mode.

Figure 3 depicts the unipolar and bipolar operation for the LTC1867. On the upper half of Figure 3, the LTC1867 samples and digitizes a sinewave on Channel 1 (CH1) that swings from 0V to 4V and measures a DC voltage of 2.5V on Channel 0 (CH0), both in unipolar mode. On the lower half of Figure 3, the ADC performs a bipolar operation with CH0 versus CH1, and

vice versa. Under these conditions the differential input signals applied to the ADC exceed the bipolar input range of ±2V. For example, in the case of CH0 minus CH1 the resulting digitized input range will be –1.5V to 2.0V.

In both unipolar and bipolar operation, $+V_{IN}$ and $-V_{IN}$ are sampled simultaneously; so common mode noise on both inputs is rejected by the truly differential inputs. In the unipolar mode, the $+V_{IN}$ range of the LTC1867 is from 0V to V_{DD} and the $-V_{IN}$ range is from 0V to $V_{DD}/2$. Some competing devices only allow the minus input to reach a few hundred millivolts to one volt above ground. By comparison the LTC1867 offers about twice the range on the minus input. This makes the LTC1867 a great choice for remote applications

where large common mode voltages can be present. In the bipolar mode, both $+V_{IN}$ and $-V_{IN}$ can accept signals from 0V to V_{DD}.

Simple Serial I/O Allows Easy Isolated or Remote Applications

The serial I/O employed by the LTC1867 and its other family members is compatible with the industry standard SPI/MICROWIRE interface. The shift clock (SCK) synchronizes the data transfer with each bit being transmitted on the falling SCK edge and captured on the rising SCK edge in both the transmitting and receiving systems. After the conversion is complete, the input word is shifted into the ADC through the SDI/SCK ports, and at the same time, data bits are

Table 2. 7-Bit Input Word (SD = MSB)

SD	OS	S1	S0	COM	UNI	SLP

1. SD = SINGLE/$\overline{\text{DIFFERENTIAL}}$ BIT
2. OS = ODD/$\overline{\text{SIGN}}$ BIT
3. S1 = ADDRESS SELECT BIT 1
4. S0 = ADDRESS SELECT BIT 0
5. COM = CH7/COM CONFIGURATION BIT
6. UNI = UNIPOLAR/$\overline{\text{BIPOLAR}}$ BIT
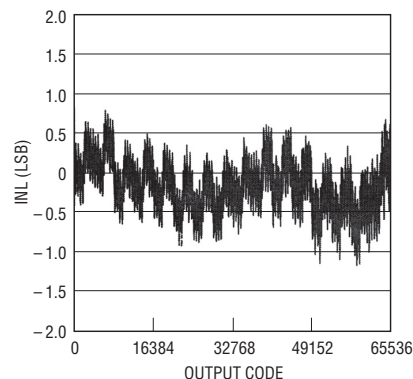7. SLP = SLEEP MODE BIT

Figure 4. The DC accuracy of the LTC1867 is shown in the INL curve. The accuracy is achieved with capacitor matching, which is very stable over time and temperature.
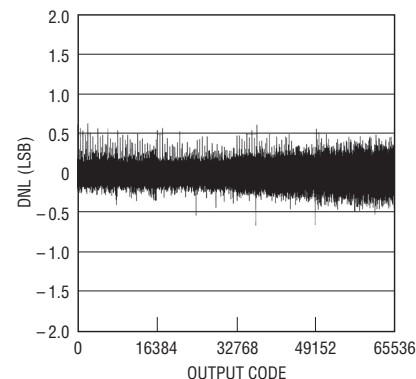

Figure 5. No missing codes and very accurate capacitor matching found in the LTC1867 DAC is illustrated by the DNL curve.
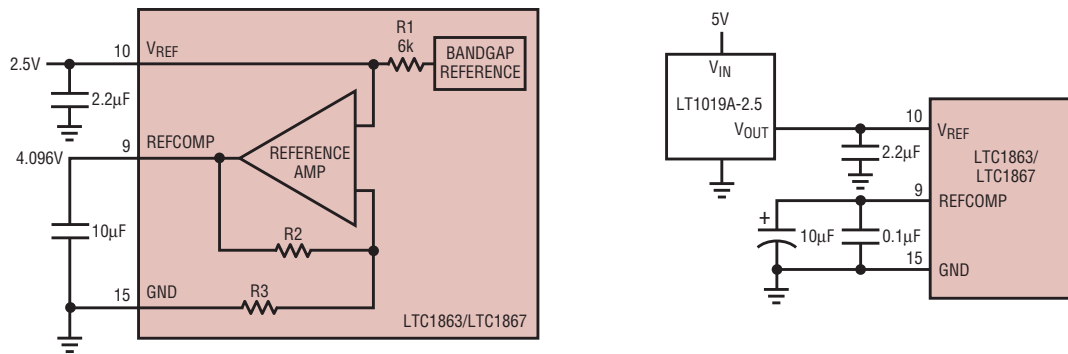
Figure 6. LTC1863/LTC1867 reference circuit. The internal reference can be overdriven by an external Reference, LT1019A-2.5 for better drift and/or accuracy performance.

released through the SDO/SCK ports. The A/D converter starts to acquire the analog input signals after reading in the 7-bit Input Word. These ADCs have an internally trimmed conversion clock which allows the sampling frequency to approach DC without affecting the conversion results. The 4-wire interface allows the LTC1867 and its siblings to fit well with isolated or remotely located applications.

Outstanding DC and AC Performance

Operating from a 5V supply and sampling up to 200ksps, the LTC1867
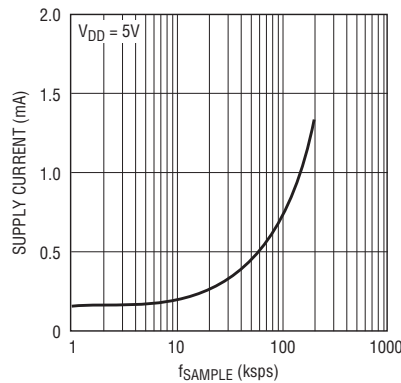

Figure 7. The LTC1867 features an Automatic Nap mode that cuts the power dissipation as the sampling frequency is reduced.

delivers 16-bit, no missing codes performance with an accurate INL specification of ±2LSB(max) in unipolar mode and ±2.5LSB(max) in bipolar mode. Typical INL and DNL plots for LTC1867 versus output code are shown in Figures 4 and 5. This performance is achieved with capacitor matching which is very stable over time and temperature.

Along with outstanding DC performance, the LTC1867 also has very good AC performance. The signal-to-noise ratio (SNR) is typically 89dB with an input range of 4V and improves to 90.5dB when an external reference
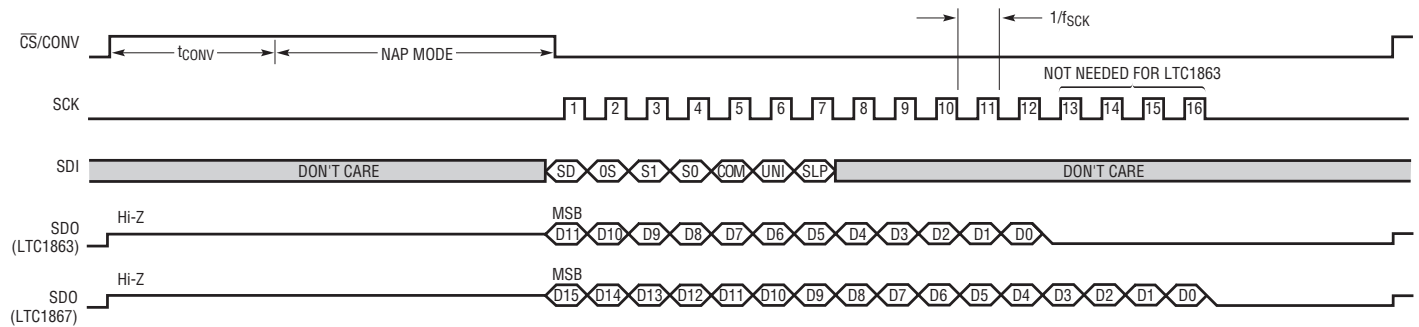

Figure 8. The Automatic Nap mode provides power reduction at reduced sample rates. This feature is activated when $\overline{CS}$/CONV remains high after the conversion is completed.
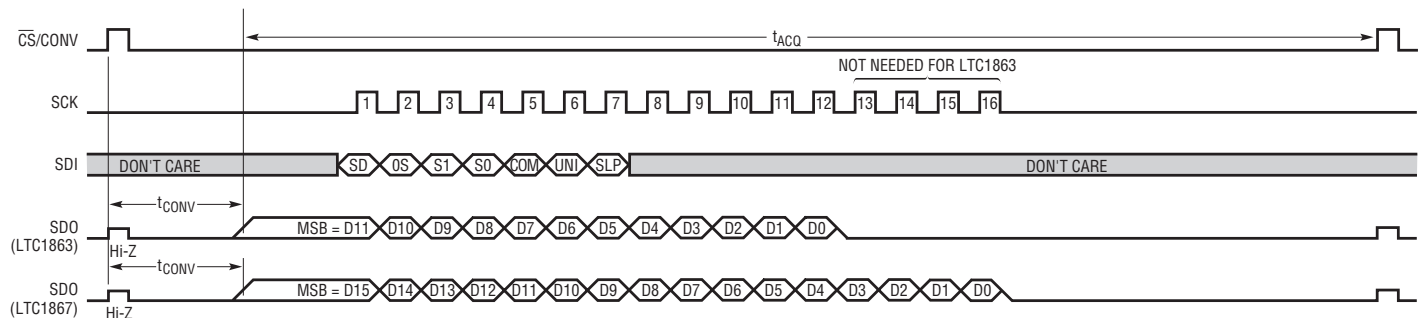

Figure 9. The Automatic Nap mode is not activated if the $\overline{CS}$/CONV pulse is shorter than the conversion time. After the conversion the ADC remains powered up.

voltage of 5V is applied to the REF-COMP pin (tie V_{REF} pin to 0V to turn off internal reference buffer).

Internal Reference

This family has an on-chip, temperature compensated, curvature corrected, bandgap reference that is factory trimmed to 2.5V for the LTC1867 and the LTC1863, and 1.25V for the LTC1867L and the LTC1863L. The reference is internally connected to a reference amplifier and is available at V_{REF} (Pin 10). A 6kΩ resistor in the LTC1867 and the LTC1863 (3kΩ resistor for the LTC1867L and the LTC1863L) is in series with the output so that it can be easily overdriven by an external reference if better drift and/or accuracy are required as shown in Figure 6. The reference amplifier gains the V_{REF} voltage by 1.638 to 4.096V at REFCOMP (Pin 9). This reference amplifier compensation pin, REFCOMP, must be bypassed with a 10µF ceramic or tantalum in parallel with a 0.1µF ceramic for best noise performance.

Low Power Improves Battery Life

The LTC1867 and LTC1863 consume only 1.3mA at a sampling rate of 200ksps. As the sampling frequency is reduced, the converters use even less supply current with the automatic Nap feature. For example, the parts draw only 760µA and 200µA at sampling frequencies of 100ksps and 10ksps, respectively.

Automatic Nap mode is active when the $\overline{CS}$/CONV pulse width is longer than the conversion time of the A/D converter. The part goes to Nap mode automatically right after a conversion is completed and remains powered down (the ADC draws 150µA in Nap mode) as long as the $\overline{CS}$/CONV stays HIGH after conversion. The internal reference, however, is still active and provides a 2.5V output. In this way, the LTC1867/LTC1863 requires no additional wake up time before the next conversion is started. Figure 7 shows how the supply current is greatly reduced as the sample rate is decreased when using this feature.

The ADCs can also go into the Sleep mode during long inactive periods. In sleep mode the internal reference is also powered down, thus reducing the draw to leakage currents of less than 1µA. The wake up time out of the sleep mode is determined by how fast the reference bypass capacitors can be charged. The wake up time can be estimated with the values of bypass capacitor on V_{REF} and the on-chip resistor between the internal reference and V_{REF} pin. For the 16-bit LTC1867L, the wake up time can be estimated as:

(resistor value) • (bypass capacitor value) • (number of time constant needed to settle to 16-bit accuracy)

or (3k • 2.2µF • 11).

Typically with bypass capacitors of 2.2µF and 10µF on the V_{REF} and REFCOMP pins, this takes about 80ms for LTC1867L. However, if an external reference is used, the wake up time is less than 10ms.

When the $\overline{CS}$/CONV pulse is shorter than the conversion time, the ADCs stay powered up and the Automatic Nap mode is not activated. In this configuration, the digital output, SDO, becomes active after the conversion is completed. Figures 8 and 9 show the timing diagrams for the two cases described.

Conclusion

The LTC1867 family packs an 8-channel analog input multiplexer, low-power A/D converter, serial I/O, and an internal reference in a narrow 16-pin SSOP package. With outstanding DC and AC performance, and equipped with the automatic Nap and Sleep modes for power reduction, these complete A/D converters can be used in many space-sensitive as well as low power applications. *LT*

The current limit fold-back circuit provides additional control during the first few switch cycles of start-up, and provides reduced short-circuit output current. When the output is at ground, the diode/resistor clamp the VC pin to a value that corresponds to 25% of the programmed maximum current. This circuit is only active with V_{OUT} close to ground, and becomes completely disabled once the output voltage rises past about 10% regulation.

8V–16V to 24V, 50W Boost Converter

The 24V Boost converter shown in Figure 6 achieves over 95% conversion efficiency at 50W with less than 20 components. Because this is a boost converter, V_{CC} is driven by the input voltage to improve efficiency and lower power dissipation. Figure 7 shows efficiency and power loss vs load current.

Conclusion

The LT3724 is a feature packed DC/DC controller that is versatile enough to be configured to control multiple converter topologies. It offers a simple and inexpensive solution to regulating system voltages at high efficiencies over a wide input voltage range and wide load range.

The integrated high voltage regulator facilitates true single-supply operation. Burst Mode operation improves efficiency during light load and no load operation. The current mode control architecture allows for simple design of the power supply control loop and excellent transient response. Continuous current sensing protects the supply from being damaged during an over current or short circuit fault condition. The innovative soft start function limits output voltage overshoot and inrush current during startup, brownout or short circuit recovery. *LT*

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Linear Charger for Nickel Cadmium or Nickel Metal Hydride Batteries Minimizes Parts Count

by Fran Hoffart

Introduction

Although rechargeable Lithium Ion and Lithium Polymer batteries have lately been the battery of choice in high performance portable products, the old workhorse nickel cadmium (NiCd) and the newer nickel metal hydride (NiMH) batteries are still important sources of portable power. Nickel based batteries are robust, capable of high discharge rates, good cycle life and are relatively inexpensive. NiMH batteries are replacing NiCd in many applications because of the higher capacity ratings (40 to 50% higher) and because of environmental concerns of the cadmium contained in NiCd cells. This article covers NiCd/NiMH battery charging basics, and introduces the LTC4060 linear battery charger.

A Primer on Charging NiCd/NiMH Batteries

The various methods for charging Nickel based batteries are categorized by speed: slow, quick and fast. The simplest type of charger is a slow charger, which applies a timer-controlled, relatively low charge current for about 14 hours. This may be too long for many portable applications. For shorter charge times, quick and fast chargers apply a constant current while monitoring the battery voltage and/or temperature to determine when to terminate or stop the charge cycle. Charge times typically range anywhere from 3 to 4 hours (quick charge) to around 0.75–1.5 hours (fast charge).

Fast and quick chargers force a constant charge current and allow the battery voltage to rise to the level it requires (within limits) to force this current. During the charge cycle, the charger measures the battery voltage at regular intervals to determine when to terminate the charge cycle. During the charge cycle, the battery voltage
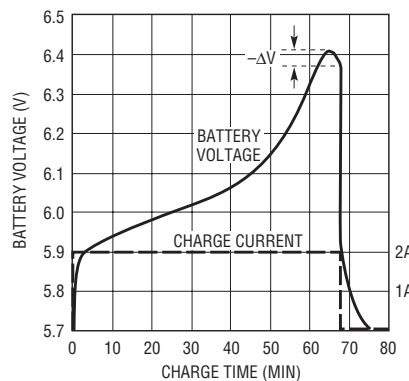

Figure 1. Typical charge profile for a 2000mAHr NiMH 4-cell battery pack charged at a 1C rate.

rises as it accepts charge (see Figure 1). Near the end of the charge cycle, the battery voltage begins to rise much faster, reach a peak, then begins to fall. When the battery voltage has dropped a fixed number of mV from the peak

(–ΔV), the battery is fully charged and the charge cycle ends.

The battery has an internal safeguard against overcharge. While the cell voltage is dropping from its peak, the battery temperature and internal pressure quickly rise. If fast charging continues for a significant amount of time after full charge is reached, the battery pressure seal may momentarily open causing gas to vent. This is not necessarily catastrophic for the battery, but when a cell vents, some electrolyte is also released. If venting occurs often, the cell will eventually fail. In addition, after venting, the seal may not close correctly and the electrolyte can dry out.

Differences Between NiCd and NiMH Batteries

The open circuit voltage (nominal 1.2V) and the end-of-life voltage (0.9V to 1V) are almost identical between the two battery types, but the charging characteristics differ somewhat. All NiCd cells can be trickle charged continuously, but some NiMH cells cannot, and may be damaged if the trickle charge is continued after reaching full charge. Also, the battery voltage profile during a fast charge cycle differs between the two battery types.

For NiMH cells, the decrease in battery voltage (–ΔV) after reaching a peak is approximately one half that of NiCd cells, thus making charge termination based on –ΔV slightly more difficult. In addition, the NiMH battery temperature rise during the charge cycle is higher than NiCd, and the higher temperature further reduces the amount of –ΔV that occurs when full charge is reached. For NiMH cells, –ΔV is almost non-existent at high temperatures for charge rates less than C/2. (See sidebar for the definition of "C"). Older batteries

and cell mismatching further reduce the already minute drops in battery voltage.

Other differences between the two chemistries include higher energy density and greatly reduced voltage depression or "memory effect" for NiMH cells, although NiCd is still preferred for high current drain applications. NiCd cells also enjoy lower self-discharge characteristics, but NiMH technology has room to improve in this regard, while NiCd technology is fairly mature.

The LTC4060 NiCd/NiMH Battery Charger Controller

The LTC4060 is a complete NiCd or NiMH linear battery charger controller that provides a constant charge current and charge termination for fast charging up to four series-connected cells. Simple to use and requiring a minimum of external components, the IC drives an inexpensive external PNP transistor to provide charge current. The basic configuration requires only five external components, although additional functions are included such as, NTC input for battery temperature qualification, adjustable recharge voltage, status outputs capable of driving an LED and shutdown and pause inputs. Selecting the battery chemistry and the number of cells to charge is accomplished by strapping pins, and the charge current is programmed using a standard value resistor. With adequate thermal management, charge current up to 2A is possible, and even higher current when using an external current sense resistor in parallel with the internal sense resistor.

What's Important When Designing a Charger Using the LTC4060?

Once the battery chemistry and number of cells are set, one must determine the correct charge current. The LTC4060 is designed for fast charging nickel-based batteries and uses $-\Delta V$ as the charge termination method. Battery temperature can also be monitored to avoid excessive battery temperature during charging, and a safety timer shuts down the

About Battery Capacity and Charge Current

The correct charge current is always related to a battery's capacity, or simply "C". The letter "C" is a term used to indicate the manufacturers stated battery discharge capacity, which is measured in mA • Hr. For example, a 2000mAHr rated battery can supply a 2000mA load for one hour before the cell voltage drops to 0.9V or zero capacity. In the same example, charging the same battery at a C/2 rate would mean charging at 1000mA (1A).

The correct charge current for fast charging NiCd or NiMH batteries is between approximately C/2 and 2C. This current level is needed for the cell to exhibit the required $-\Delta V$ inflection that occurs when the cell reaches full charge, although charging at 2C may cause excessive battery temperature rise, especially with small, high capacity NiMH cells. Because of chemical differences between the two battery chemistries, NiMH cells generate more heat when fast charging.

charger if charge termination does not occur. The typical fast charge voltage profile (the rapid rise, then drop in battery voltage ($-\Delta V$) near the end of the charge cycle) only occurs at a relatively high charge current. If the charge current is too low, the battery voltage does not produce the required drop in battery voltage after reaching a peak, which is necessary for the LTC4060 to terminate the charge cycle. At very low charge current, $-\Delta V$ does not occur at all. On the other hand, if the charge current is too high, the battery may become excessively hot requiring an NTC thermistor located

near the battery to pause the charge cycle allowing the battery to cool down before resuming the charge cycle.

A Typical LTC4060 Charge Cycle

With sufficient input voltage applied, no battery connected and the correct charge current, charge time and thermistor connections in place, the charger's output voltage is very close to the input voltage. Connecting a discharged battery to the charger pulls down the charger's output voltage below $1.9 \cdot V_{CELL}$ (V_{CELL} is the total battery voltage divided by the number
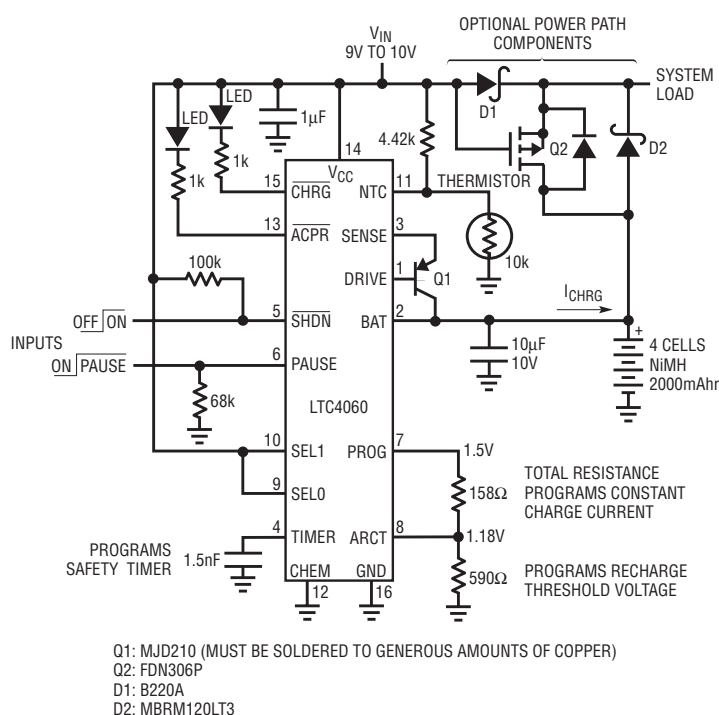

Figure 2. 4-cell 2A NiMH battery charger with NTC thermistor and power path control

of cells being charged) thus starting a charge cycle.

If the battery temperature, as measured by the NTC thermistor, is outside a 5°C to 45°C window, the charge cycle pauses and no charge current flows until an acceptable temperature is reached. When the battery temperature is within limits, the battery voltage is measured and must be below the max limit.

If V_{CELL} is below 900mV, the charger begins a trickle charge of 20% of the programmed charge current until the voltage exceeds 900mV, at which point the full programmed charge current begins. Several hundred milliseconds after the charge cycle begins, if the battery voltage exceeds 1.95V, the charge cycle stops. This overvoltage condition usually means the battery is defective requiring that the charger be manually reset by replacing the battery, toggling the shutdown pin, or removing and reapplying power.

Once the programmed constant charge current starts flowing, a period of time known as "hold-off-time" begins. This hold-off-time ranges from 4 minutes to 15 minutes depending on the charge current and charge time settings. During the hold off time, the –ΔV termination is disabled to prevent false charge termination. A battery that is deeply discharged or has not been charged recently may exhibit a drop in battery voltage during the early portion of the charge cycle, which could be mistaken for a valid –ΔV termination.

During the charge cycle, the battery voltage slowly rises. When the battery approaches full charge, the battery voltage begins to rise faster, reaches a peak, then begins to drop. The charger continuously samples the

battery voltage every 15 to 40 seconds, depending on charge current and timer settings. If each sampled voltage reading is less than the previous reading, for four consecutive readings, and the total drop in battery voltage exceeds 8mV/cell for NiMH or 16mV/cell for NiCd, the charge current stops, ending the charge cycle. The open drain output pin "CHRG", which was pulled low during the charge cycle, now becomes high impedance.

A user programmable recharge feature starts a new charge cycle if the battery voltage drops below a set voltage level because of self-discharge or a load on the battery. Also, if a fully charged battery greater than 1.3V is connected to the charger, the –ΔV termination detection circuit is enabled immediately with no hold-off-time, thus shortening the charge cycle for a battery that is already close to full charge.

If the battery reaches approximately 55°C during the charge cycle, the charger pauses until the temperature drops to 45°C, then resumes charging until the –ΔV termination ends the charge cycle. If no –ΔV termination takes place, the safety timer stops the charge cycle. If the timer stops the charge cycle, it is considered a fault condition and the charger must be reset by removing and replacing the battery, toggling the SHDN pin or toggling the input power to the charger.

Watch Out for These Pitfalls

Don't connect a load directly to the battery when charging. The charge current must remain relatively constant for the –ΔV charge termination to be effective. Loads with changing

> *The LTC4060 is a complete NiCd or NiMH linear battery charger controller that provides a constant charge current and charge termination for fast charging up to four series-connected cells.*

current levels result in small changes in battery voltage which can trigger a false –ΔV charge termination. For applications that require a load, refer to the power path components shown in Figure 2. When the input voltage is present, the load is powered from the input supply through Schottky diode D1 and the battery is isolated from the load. Removing the input voltage pulls the gate of Q2 low, turning it on providing a low resistance current path between the battery and the load.

Minimize the DC resistance between the charger and the battery. Some battery holders have springs and contacts that have excessive resistance. The increased resistance in series with the battery can prevent a charge cycle from starting because of a battery overvoltage condition once the full charge current begins. Poorly constructed battery holders can also produce false charge termination if battery movement generates a premature –ΔV reading.

Unlike Lithium Ion cells that can be paralleled for increased capacity, NiCd or NiMH cells should not be paralleled, especially when fast charging. Interaction between the cells prevents proper charge termination. If more capacity is required, select larger cells.

Not all NiCd or NiMH batteries behave the same when charging. Manufacturers differ in materials and construction resulting in somewhat different charge voltage profiles or amount of heat generated. A battery can be designed for general purpose use, or optimized for high capacity, fast charge rate, or high temperature operation. Some batteries may not be designed for high current (2C) charge rates resulting in high cell temperature when charging. Also, most new cells are not completely formed and require some conditioning before they reach their rated capacity. Conditioning consists of multiple charge and discharge cycles.

A thermistor mounted near the battery pack, preferably making contact with one or more of the cells, is highly recommended, both as a safety feature and to increase battery lifetime. Unlike

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Determine the Real Internal Resistance of a Battery

by Jim Williams

Introduction

An accurate measure of a battery's true internal resistance can reveal much about its condition or its suitability for an application, but measurement is not as easy as hooking up a precision ohmmeter. Inherent capacitance of a battery reduces the accuracy of measurements taken with a common AC-based milliohmmeters operating in the kHz range. Figure 1, a very simplistic battery model, shows a resistive divider with a partial shunt capacitive term. This capacitive term introduces error in AC based measurement. Also, the battery's unloaded internal resistance can significantly differ from its loaded value. A realistic determination of internal resistance must be made under loaded conditions at or near DC.

Figure 2's circuit meets these requirements, permitting accurate internal resistance determination of batteries up to 13V over a range of 0.001Ω to 1.000Ω. A1, Q1 and associated components form a closed loop current sink which loads the battery
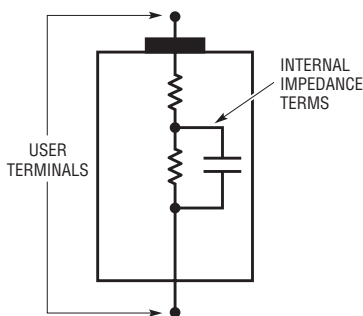

Figure 1. Simplistic model shows battery impedance terms include resistive and capacitive elements. Capacitive component corrupts AC based measurement attempts to determine internal DC resistance. More realistic results occur if battery voltage drop is measured under known load.

via Q1's drain. The 1N5821 provides reverse battery protection.

The voltage across the 0.1Ω resistor, and hence the battery load, is determined by A1's "+" input voltage. This potential is alternately switched, via S1, between 0.110V and 0.010V derived from the 2.5V reference driven 3-resistor string. S1's 0.5Hz square wave switching drive comes from the CD4040 frequency divider. The result of this action is a 100mA

biased, 1A, 0.5Hz square wave load applied to the battery. The battery's internal resistance causes a 0.5Hz amplitude modulated square wave to appear at the Kelvin-sensed, S2-S3-A2 synchronous demodulator. The demodulator DC output is buffered by chopper stabilized A2, which provides the circuit output. A2's internal 1 kHz clock, level shifted by Q2, drives the CD4040 frequency divider. One divider output supplies the 0.5Hz square wave; a second 500Hz output activates a charge pump, providing a –7V potential to A2. This arrangement allows A2's output to swing all the way to zero volts.

The circuit pulls 230µA from its 9V battery power supply, permitting about 3000 hours battery life. Other specifications include operation down to 4V with less than 1mV (0.001Ω) output variation, 3% accuracy and battery-under-test range of 0.9V–13V. Finally, note that battery discharge current and repetition rate are easily varied from the values given, permitting observation of battery resistance under a variety of conditions.

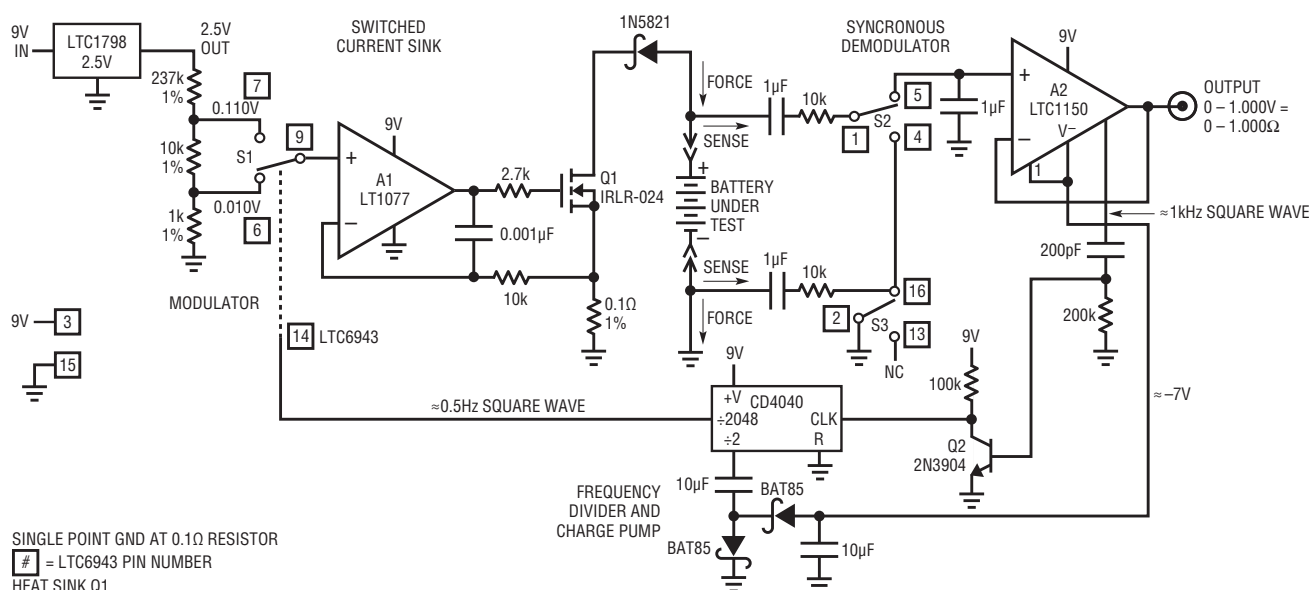Figure 2. Battery internal resistance is determined by repetitively stepping calibrated discharge current and reading resultant voltage drop. S1 based modulator, clocked from frequency divider, combines with A1-Q1 switched current sink to generate stepped, 1A battery discharge cycles. S2-S3-A2 synchronous demodulator extracts modulated voltage drop information, provides DC output calibrated in Ohms.

Digitally Programmable Output Monolithic Buck Regulator with Built-In DAC and I²C Interface
by Earl Barber

Introduction

A small package and high efficiency make Linear Technology's new LTC3447 buck regulator an ideal choice for portable devices using lithium-ion batteries. The tiny 3mm × 3mm DFN package supplies up to 600mA of current over an I²C programmable output range of 0.69V to 2.05V. An internal 6-bit DAC gives the designer the flexibility needed to control the supply voltage for various modes of operation.

LTC3447 Features Include:

❏ Soft Start — Limits peak inductor current for a short period when the regulator is first enabled.

❏ Frequency Foldback — Reduces oscillator frequency when the regulated voltage is below the desired operating point. This allows time for the inductor current to discharge fully and prevent thermal runaway.

❏ Over Temperature Protection — Turns off internal switching FETs until the operating temperature returns to a normal level.

❏ Power Good Reporting — Reports when the regulated voltage is either under-voltage or over-voltage. This feature can be disabled via the I²C interface.

❏ Burst Mode Operation — Improves efficiency at light loads to improve battery life. When a light load is detected, the regulator enters a highly efficient mode whose quiescent current is 33μA.

Minimal Space

Figures 1 and 2 show the LTC3447 powered from a single Lithium-Ion battery. To minimize critical board real estate, only two ceramic capacitors, a single inductor, and a single resistor are required for operation. The LTC3447 regulator is internally
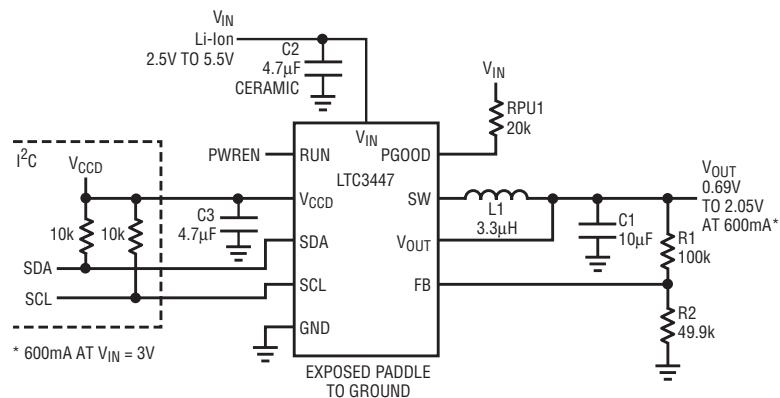

Figure 1. A typical Li-Ion-to-programmable-output application suitable for powering a microprocessor
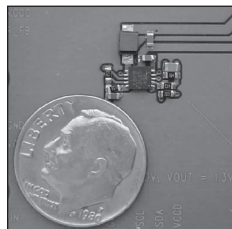

Figure 2. Very little space is needed for a programmable output solution. This circuit includes optional start-up resistors and I²C pull-up resistors.

compensated to further reduce the need for additional external components. Optional external resistors can be used when a start-up voltage other than 1.38V is desired. When using the optional start-up resistors, the regulated voltage can be set to a value outside of the normal DAC output range. Once the internal DAC is changed, the regulated output voltage remains between 0.69V and 2.05V.

The Efficiency Advantage

In an effort to extend battery life, many μProcessors use a variety of power modes. Reducing the supply voltage to circuits not in use and then increasing the supply voltage when in use is a common technique. The LTC3447

is designed to easily accomplish such tasks thru its I²C interface. The 6-bit DAC allows the designer to easily change the supply voltage level from 0.69V to 2.05V. Another technique is to simply reduce the current load of the μprocessor. The LTC3447 can sense light load conditions and enter power-saving Burst Mode operation for further power savings. Using the LTC3447 to combine both these techniques can greatly extend the life of the battery. Figure 3 shows the efficiency of the LTC3447. Notice the jump in efficiency for light load currents when Burst Mode operation is enabled. *LT*
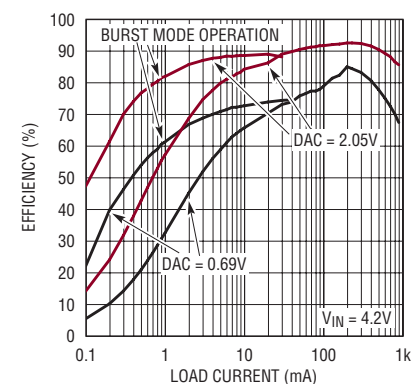

Figure 3. Efficiency of the circuit in Figure 1

Connect High Impedance Sensors Directly to an Easy Drive Delta Sigma ADC

by Mark Thoren

Delta Sigma ADCs are accurate and have high noise immunity, making them ideal for directly measuring many types of sensors. Nevertheless, input sampling currents can overwhelm high source impedances or low-bandwidth, micropower signal conditioning circuits. The LTC2480 family of Delta Sigma converters solves this problem by balancing the input currents, thus simplifying or eliminating the need for signal conditioning circuits.

A common application for a delta sigma ADC is thermistor measurement. Figure 1 shows the LTC2480 connections for direct measurement of thermistors up to 100kΩ. Data I/O is through a standard SPI interface, and the sampling current in each input is approximately

$$\frac{\left(\dfrac{V_{REF}}{2}\right) - V_{CM}}{1.5M\Omega}, \text{ where } V_{CM} = \frac{V_{IN^+} + V_{IN^-}}{2}$$

or about 1.67μA when V_{REF} is 5V and both inputs are grounded.

Figure 2 shows how to balance the thermistor such that the ADC input current is minimized. If the two reference resistors are exactly equal, the input current is exactly zero and no errors result. If the reference resistors have a 1% tolerance, the maximum error in the measured resistance is
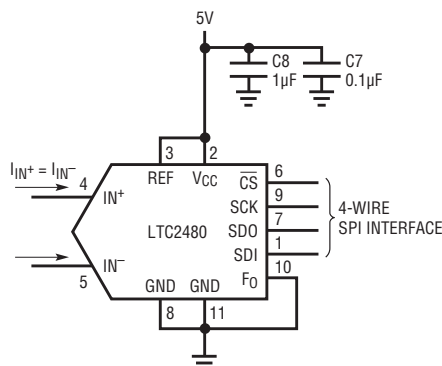

Figure 1. LTC2480 connections

1.6Ω due to the slight shift in common mode voltage; far less than the 1% error of the reference resistors themselves. No amplifier is required, making this an ideal solution in micropower applications.

The LTC2480 family of Delta Sigma converters balances input sampling currents, thus simplifying or eliminating the need for signal conditioning circuits.

It may be necessary to ground one side of the sensor to reduce noise pickup or simplify wiring if the sensor is remote. The varying common mode
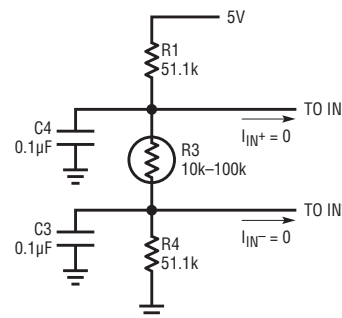

Figure 2. Centered sensor

voltage produces a 3.5kΩ full-scale error in the measured resistance if this circuit is used without buffering.

Figure 3 shows how to interface a very low power, low bandwidth op amp to the LTC2480. The LT1494 has excellent DC specs for an amplifier with 1.5μA supply current—the maximum offset voltage is 150μV and the open loop gain is 100,000—but its 2kHz bandwidth makes it unsuitable for driving conventional delta sigma ADCs. Adding a 1kΩ, 0.1μF filter solves this problem by providing a charge reservoir that supplies the LTC2480's instantaneous sampling current, while the 1kΩ resistor isolates the capacitive load from the LT1494. Don't try this with an ordinary delta sigma ADC—the sampling current from ADCs with specifications similar to the LTC2480 family would result in a 1.4mV offset and a 0.69mV full-scale error in the circuit shown in Figure 3. The LTC2480's balanced input current allows these errors to be easily cancelled by placing an identical filter at IN⁻. ![LT logo]
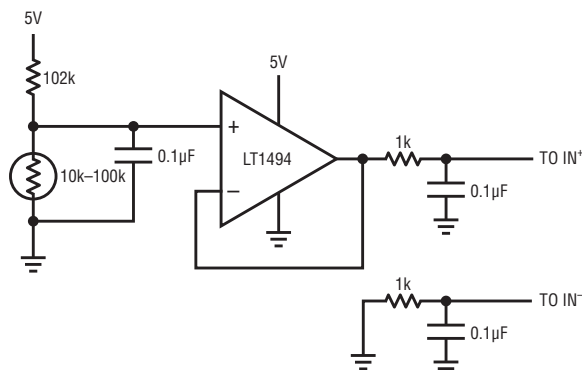

Figure 3. Grounded, buffered sensor

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Dual Switching Converter Provides Two Outputs of Any Polarity

by Jesus Rosales

Op amps, CCD imagers, LCDs, medical diagnostic equipment and a host of other circuits require dual power supplies. Both supplies may be positive, both negative, or they may be opposite polarity. Dual supplies are implemented in a variety of ways, including using two converters, tapping off the switch with capacitors and diodes, or using multi-winding transformers. Each of these solutions adds unnecessary cost, size and complexity, especially now that there is a simple, single device solution available with the LT3471.

Simplicity and versatility are two features that are often at odds in the world of switching regulators—simplicity usually means fewer components; versatility more. The LT3471 turns this idea on its head by offering a versatile feature set with a minimal number of components in a dual-output converter.

Consider the circuit in Figure 1. With a Li Ion battery input, this converter provides two positive supplies: a 5V output and a 12V output. Only one input filter capacitor is required. Both outputs are independently controlled, but the same clock runs both switchers to avoid any interference (beat frequency) between them.

The circuit in Figure 2 provides two output voltages of opposite polarity: a 15V output and a –8V output. This design uses very small inductors, measuring 3.2mm by 2.5mm with a profile of 1.7mm. In applications where circuit size is critical, this circuit can fit in an area as small as 0.16 square inches. The saturation current in the inductors used dictates the maximum available current to the values shown in the schematic. If more current is needed, the LT3471 can deliver by choosing bigger inductors. As in Figure 1, the circuit in Figure 2 provides two outputs requiring only one input filter capacitor.
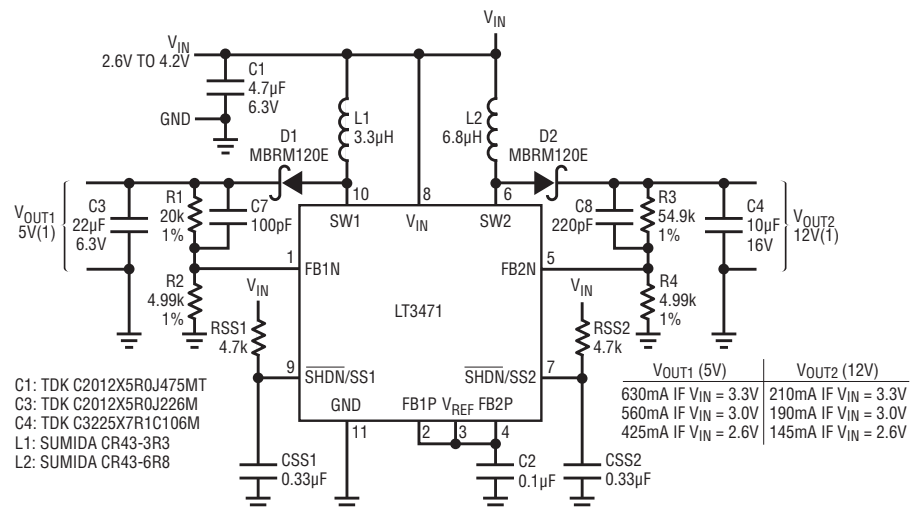
Figure 1. A 1.2MHz, Li-ion to 5V and 12V Converter
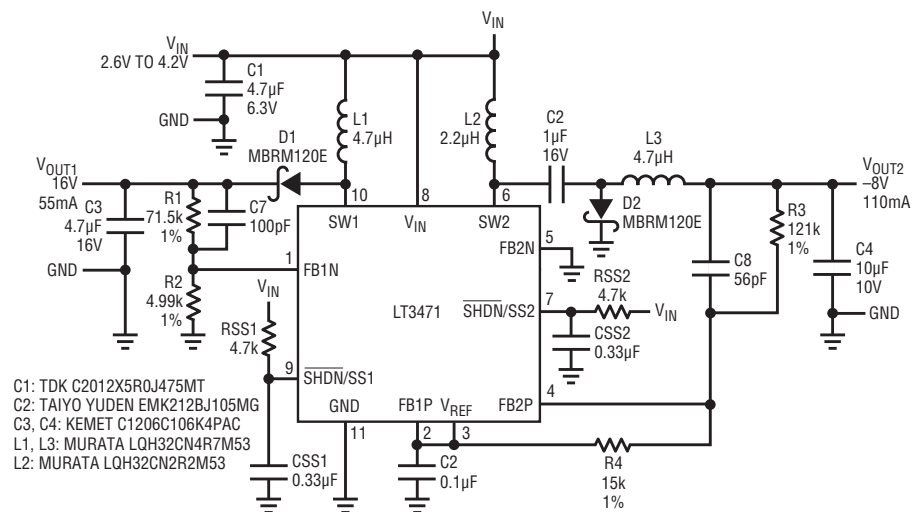
Figure 2. A 1.2MHz, Li-ion to 15V at 55mA and –8V at 110mA converter
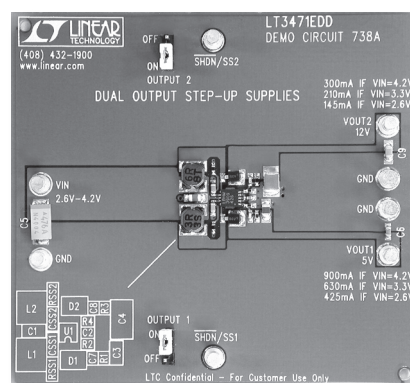
Figure 3. A compact, 1.2MHz dual output converter for Li-ion to 5V and 12V.

In situations where inrush current is a problem, the LT3471 contains a capacitor-programmable soft start feature that allows the designer to individually program the ramp rate of each output. Figure 3 shows a typical layout. ☰

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Micropower SOT-23 Inverting DC/DC Converter Extends Battery Life in Space-Sensitive Applications
by Eric Young

Introduction

Low power negative bias supplies are commonly used in many of today's handheld products for imaging and display modules. As is the case with all portable products, small size and efficient operation are top requirements. The LT3483 steps in to fill this need with a minimum footprint, low profile negative supply that yields long battery life.

One of the strengths of the LT3483 is its versatility. It can be used for inverting step-up (boost) or for inverting step-down applications. It features an input range of 2.5V to 16V, so the device works well with a range of battery types and configurations. Its internal 40V switch and integrated 40V Schottky rectifier allow it to generate output voltages to ±38V.

The LT3483 also includes features to maximize battery run time. At no load conditions, the device draws only 36µA of battery current to maintain the output or outputs in regulation. The current limited fixed off-time control scheme delivers power-on-demand to achieve high efficiency operation over a wide range of load currents. A shutdown pin disables the device and reduces quiescent current to less than 1µA. During operation, the shutdown pin draws only 5µA from a 3.6V supply.

Simple, Accurate Negative Regulators

It is easy to set the negative output voltage of the LT3483 inverting converter, because there is no need to compensate for a variable FB input bias current. The FB input is referenced to GND and features a 2% accurate, temperature compensated 10µA reference source current. An external resistor between FB and the negative output sets the output voltage within 2% plus resistor tolerances. By
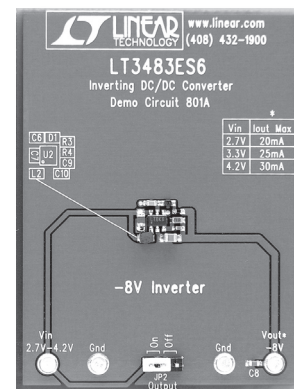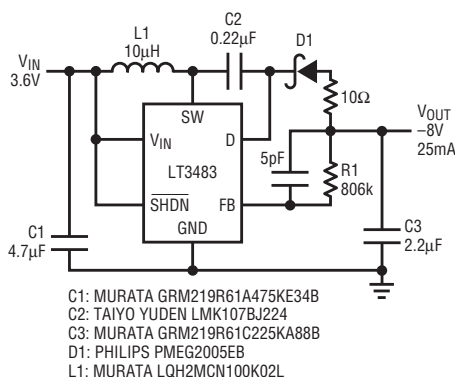

Figure 1. Low profile 3.6V to –8V inverting converter in 50mm²

eliminating the untrimmed current sourced by the negative FB (NFB) pin of other inverting regulators, calculation of the feedback resistor has been simplified as follows:

$$V_{OUT} = -10\mu A \cdot R$$

The resulting output voltage is therefore more accurate and less current flows into the feedback divider.

–8V at 25mA in 50mm²

The 200mA current limit and 300ns off-time allow the use of tiny low profile inductors and low profile ceramic capacitors. Figure 1 shows a bias supply useful for CCD and OLED applications that produces a well regulated –8V supply at up to 25mA from 3.6V using as little as 50mm² of board space. All components in this design are less than 1mm in height. While the inductor usually dominates board area and pro-
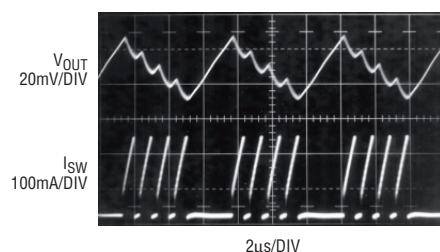
Figure 2. Output ripple of the 3.6V to –8V inverter at 15mA is 40mV.

file, regulators built with the LT3483 are able to take maximum advantage of smaller size low profile inductors such as the Murata LQH2 series—with minor reductions in output power capability and efficiency. The resulting converter circuits squeeze the most performance out of the smallest spaces. The –8V converter also uses low profile ceramic capacitors for the input, output and flying capacitors. Figure 2 shows that the output voltage ripple of the –8V converter at 15mA is about 40mV. Switching at no load, the converter circuit draws 79µA from the battery.

±15V at 5mA in 90mm²

A typical LCD application requires both a positive and a negative voltage. The LT3483 circuit shown in Figure 3 provides a 15V and a –15V output from a 3.6V supply. The –15V rail is generated using an inverting charge pump and is regulated through the feedback resistor. The quasi-regulated 15V is generated by a charge pump tapped from the switch node.

With this circuit configuration, it is straightforward to generate other complementary pairs of regulated outputs besides ±15V. All components in this design are low profile (<1mm) and the circuit makes efficient use of

Figure 3. Compact, high efficiency LCD power supply yields 5mA at ±15V in less than 90mm².

C1, C2: TAIYO YUDEN UMK212BJ104KG
C3, C4: TAIYO YUDEN TMK212BJ105KG
D1, D2, D3: PHILIPS PMEG2005EB
L1: MURATA LQH2MCN100

Figure 4. Efficiency of ±15V converter at V_{IN} = 3.6V.

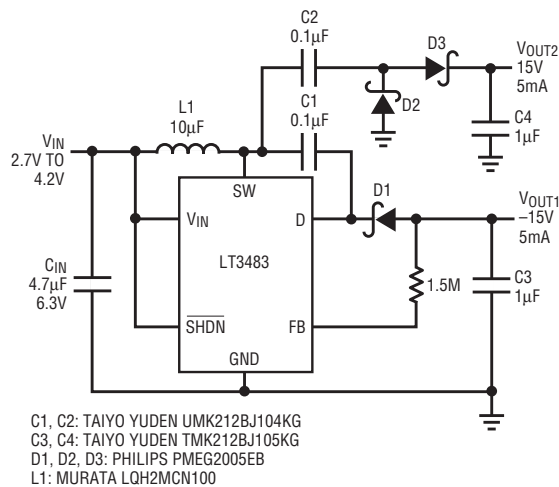board space. The additional components for the charge pump are offset by the internal feedback resistor and integrated Schottky diode. During shutdown, both the positive and negative loads are disconnected from the battery, which increases battery run time. Switching with no load, the circuit draws 135µA from a 3.6V supply. The advantages offered by this circuit are low quiescent current, low parts count, and small footprint.

–5V at 100mA from 12V

The LT3483 can also regulate a negative output voltage that is smaller in magnitude than the input voltage, useful for systems that employ a 12V

lead-acid battery as a standby power supply. Figure 5 shows the LT3483 in a robust step-down backup supply, which uses a small, low profile 1:1 coupled inductor in an inverting fly-back configuration.

One of the strengths of the LT3483 is its versatility. It can be used for inverting step-up or for inverting step-down applications.

The LT3483 can be always active, ready if primary power fails, drawing only 45µA from the battery. If the normal power supply fails, the backup

circuit using the LT3483 immediately delivers up to 100mA at –5V. In the dual inductor configuration, the LT3483 is also protected against grounding of the output. A proprietary current limiting scheme prevents the buildup of excessive switching currents which could cause damage to components in the power path.

Conclusion

The LT3483 provides a very compact, low quiescent current step-up or step-down DC/DC inverter solution for a wide input voltage range of 2.5V to 16V and outputs to –38V, making it a good fit for a variety of portable or battery backup applications.

Figure 5. –5V step-up/step-down converter

C1: TAIYO YUDEN EMK316BJ475ML
C2: TAIYO YUDEN JMK316BJ106ML
L1A, L1B: WURTH 744876100
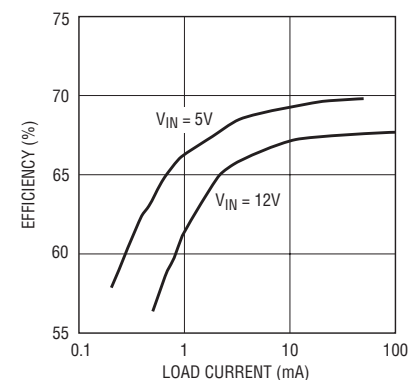
Figure 6. Efficiency of –5V step-up/step-down converter

Lithium Ion batteries that exhibit very little temperature rise when charging, Nickel based batteries will heat up during the charge cycle, especially NiMH batteries. Minimizing the length of time the battery is exposed to elevated temperature extends battery lifetime.

Conclusion

NiCd and NiMH batteries are ideal sources of rechargeable power for many portable products and backup applications. This article helps to familiarize the user with some of the charging characteristics of nickel

based batteries and how they apply to the LTC4060 charger. Charging NiCd and NiMH batteries correctly and safely is simplified using the LTC4060 linear battery charger controller.

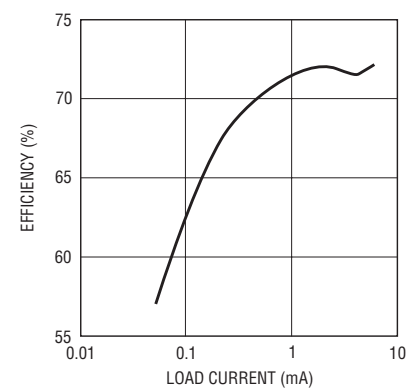# OLED Driver with Output Disconnect and Automatic Burst Mode Improves Standby Mode Efficiency

by David Kim

Introduction

The LT3473 is a micropower step-up DC/DC converter designed to drive self-luminous organic light-emitting diode or OLED display. The LT3473 features an integrated output disconnect switch that prevents leakage from OLED display during standby or shutdown mode by isolating the OLED display from input supply. The LT3473 also features an automatic burst mode, which allows outputs to be regulated with minimum circuit operation to maximize the light load efficiency. The small DFN package (3mm × 3mm), high level of integration and constant switching frequency yield a tiny solution size.

Some OLED applications require intermediate bias voltages for enhancing the display refreshing rate, such as in passive matrix OLED displays, the LT3473A includes two NPN transistors for generating two additional bias voltages.

OLED Bias Supply

Figure 1 shows an OLED bias supply solution ideally suited for handheld and other battery powered portable devices. Using the internal 1A switch, the circuit is capable of delivering 25V at up to 80mA from a Li-Ion cell (3~4.2V) input. An LT3473-based OLED bias supply requires only a few external components, because most functions are integrated into the part, including: the power switch, a Schottky diode, the output disconnect switch, a reference override, power good indication and optimized loop compensation. As a result, the circuit in Figure 1 only requires less than 50mm^2 of PC board space.

For simple dimming or contrast adjustment, the LT3473 solution has an auxiliary reference input (CTRL pin) that allows the user to override the internal 1.25V feedback reference

C$_{IN}$: TAIYO YUDEN JMK107BJ475
C$_{INT}$: TAIYO YUDEN GMK212BJ474
C$_{OUT}$: TAIYO YUDEN GMK325BJ225
L1: TOKO A915AY-6R8M (TYPE D53LC)
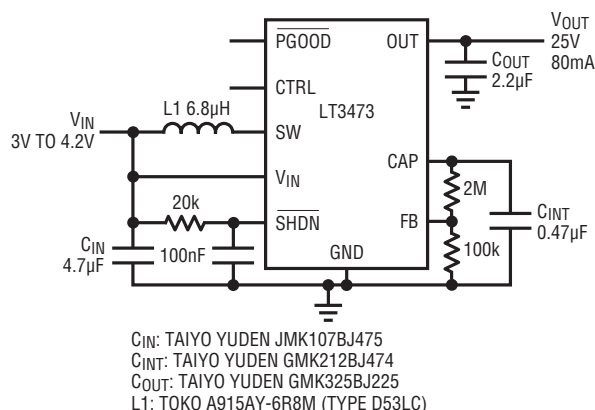
Figure 1. Space saving OLED bias supply

voltage with any lower value, allowing full control of the output voltage.

Power Good indication is also integrated in the LT3473 solution. When

The small DFN package (3mm × 3mm), high level of integration and constant switching frequency yield a tiny OLED solution size.

the output voltage reaches 90% of the set value, the open collector logic at power good pin starts to sink current to indicate that output voltage has reached power good stage.
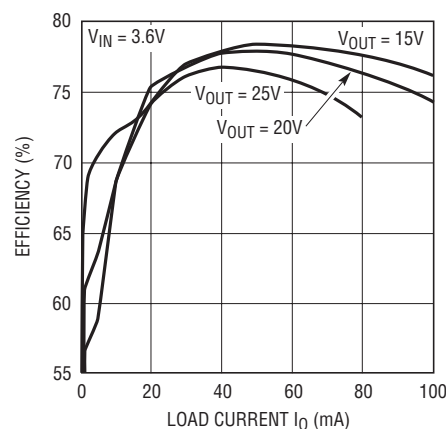
Figure 2. Efficiency of OLED bias supply

The efficiency shown in Figure 2 remains above 75% over a load current range of 20mA–70mA. Figure 2 also shows efficiency for 15V and 20V outputs. For a 15V output, the circuit is capable of generating 100mA of output current above 75% efficiency.

Conclusion

The LT3473 offers highly integrated solution for OLED bias applications. Key features include output disconnect, automatic burst mode for light load, reference override and auxiliary intermediate bias output (LT3473A) for overall efficiency and performance of OLED bias applications. The resulting small circuit size and high efficiency makes LT3473 an ideal solution for space-conscious portable device applications such as cellular phones and other handheld applications. ![LT]

For further information on any of the devices mentioned in this issue of *Linear Technology*, use the reader service card or call the LTC literature service number:

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Ask for the pertinent data sheets and Application Notes.

New Device Cameos

Dual, Low Voltage, No R$_{SENSE}$ Synchronous Controller in 4mm x 4mm QFN

The LTC3736-2 is the newest addition to the LTC3736 family of dual, 2-Phase, No R$_{SENSE}$™ step-down DC/DC synchronous controllers with output tracking. The LTC3736-2 uses a constant frequency, peak current mode architecture with MOSFET V$_{DS}$ sensing, improving efficiency and eliminating the need for current sense resistors. The two controllers are operated 180° out of phase, reducing the input ripple current and required input capacitance. The LTC3736-2 can regulate output voltages as low as 0.6V from input supplies from 2.75V to 9.8V, making it ideal for 3.3V and 5V rails, as well as many different battery chemistries.

Compared to the original LTC3736, the LTC3736-2 features a 0.6V ±1% voltage reference (over the full temperature range from –40°C to +85°C). It also has a higher adjustable current limit range to allow it to be used with a larger selection of power MOSFETs. The LTC3736-2 can be configured for pulse skipping (discontinuous) or forced continuous operation at light loads.

The LTC3736-2 keeps many of the other popular features of the LTC3736 family, including selectable frequency up to 750kHz, synchronizable frequency from 250kHz to 850kHz using its PLL, a power good output voltage indicator, supply tracking, internal soft-start, optional external soft-start, and 9µA shutdown current. The LTC3736-2 is available in the tiny 4mm × 4mm QFN package.

Dual/Quad 18MHz, Low Noise, Rail-to-Rail, CMOS Op Amps

The LTC6241 and LTC6242 are dual and quad low noise, low offset, rail-to-rail output, unity gain stable CMOS op amps that feature 1pA of input bias current. The 0.1Hz to 10Hz noise of only 550nV$_{P-P}$, along with an offset of just 125µV make them uncommon among traditional CMOS op amps. Additionally, noise is guaranteed to be less than 10nV/√Hz at 1kHz. An 18MHz gain bandwidth, and 10V/µs slew rate, along with the wide supply range and low input capacitance, make them perfect for use as fast signal processing amplifiers.

These op amps have an output stage that swings within 30mV of either supply rail to maximize the signal dynamic range in low supply applications. The input common mode range extends to the negative supply. They are fully specified on 3V and 5V, and an HV version guarantees operation on supplies up to ±5.5V. The LTC6241 is available in the 8-pin SO, and for compact designs it is packaged in the tiny dual fine pitch leadless (DFN) package. The LTC6242 is available in the 16-PinSSOP as well as the 5mm × 3mm DFN package.

Inductorless Multi-Mode High Current LED Charge Pump Delivers 700mA of Current with Over 90% Efficiency

The LTC3215 is a fractional charge pump, high current white LED driver that delivers up to 700mA of LED current. Its high efficiency multi-mode architecture automatically switches between 1x, 1.5x or 2x boost modes by monitoring the voltage across the LED current source and switching modes only when I$_{LED}$ dropout is detected. This enables the LTC3215 to maximize efficiency (up to 92%) throughout the entire Li-Ion operating range. A 900kHz switching frequency and a low external parts count (two flying capacitors, two programming resistors and two bypass capacitors at V$_{IN}$ and CPO) provide a very tiny footprint and cost-effective solution, ideally suited for video and flash applications in camera phones and other portable lighting applications.

Built-in soft-start circuitry prevents excessive inrush current during start-up. High switching frequency enables the use of small external capacitors. LED current is programmed with an external resistor. The LED is disconnected from V$_{IN}$ during shutdown.

An ultralow dropout current source maintains accurate LED current at very low I$_{LED}$ voltages. Automatic mode switching optimizes efficiency by monitoring the voltage across the LED current source and switching modes only when I$_{LED}$ dropout is detected. The LTC3215 is available in a low profile 3mm × 3mm 10-Lead DFN package.

1.5GHz to 2.4GHz High Linearity Direct Quadrature Modulator

The LT5528 is a direct I/Q modulator designed for high performance wireless applications, including wireless infrastructure. It allows direct modulation of an RF signal using differential baseband I and Q signals. It supports PHS, GSM, EDGE, TD-SCDMA, CDMA, CDMA2000, W-CDMA and other systems. It may also be configured as an image reject up-converting mixer, by applying 90° phase-shifted signals to the I and Q inputs. The I/Q baseband inputs consist of voltage-to-current converters that in turn drive double-balanced mixers. The outputs of these mixers are summed and applied to an on-chip RF transformer, which converts the differential mixer signals to a 50Ω single-ended output. The four balanced I and Q baseband input ports are intended for DC coupling from a source with a common-mode voltage level of about 0.5V. The LO path consists of an LO buffer with single-ended input, and precision quadrature generators that produce the LO drive for the mixers. The supply voltage range is 4.5V to 5.25V.

Low Power 125Msps 14-bit Wideband ADC Improves Base Station Power Efficiency and Battery Life for Portable Electronics

The LTC2255 is a 125Msps, 14-bit Analog to Digital Converter (ADC) that features excellent AC performance and extremely low power. Outperforming

its nearest 14-bit competitor, the LTC2255 consumes 49% less power at just 395mW, significantly lowering the power budget and thermal considerations required for multiple channel devices. This provides a significant advantage in applications where efficiency and cooling is critical, such as satellite receivers, wireless base stations and portable electronics. As part of an extensive pin-compatible family, the LTC2255 comes in a conveniently small 5mm × 5mm QFN package with integrated bypass capacitors, requiring only a small number of tiny external components. The LTC2255 eliminates the need for large and costly decoupling capacitors, affording the smallest solution size available, which eases PCB space constraints and allows for more compact, cost effective designs. With its small dimensions, low power and reduced external component requirement, designers can easily fit four LTC2255 ADCs where just one competing solution would fit.

The LTC2255 is well placed to meet the needs of 3G and emerging 4G technologies, WiMAX and other wideband wireless applications where high performance ADCs play a key role in handling the demands of increasing network traffic. For wireless base station system designers, reduced power consumption is an important design consideration in helping to lower overall system operation costs. In addition, the combination of high sampling rate, low current and 14-bit resolution make it ideally suited to battery powered, high performance test and instrumentation equipment.

The LTC2255 offers exceptional low-level input signal performance due to its high linearity, and it is designed with good margin relative to the sample rate for reliable performance over a wide temperature range. At 125Msps sampling rate, it achieves excellent AC performance with 72.1dB SNR and 85dB SFDR at 70MHz. *LT*

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those required for input and output decoupling. The LTC3780 allows the designer to avoid these expensive, space-wasting complexities while increasing efficiency.

Short Circuit Protection

The basic boost regulator topology provides no short circuit protection. When the output is pulled low, a large current can flow from the input to the output. Nevertheless, if an overload causes an LTC3780 circuit to reach current limit, current foldback prevents the overload from carrying over to the input without shutting down the whole circuit. Figure 14 shows the result: the converter is forced into buck mode, and the duty cycle of SW2 is reduced such that the voltage at SW2 continues to swing between V_{IN} and ground. V_{IN} remains solid since current foldback limits the inductor current, so the supply only draws 100mA more than it would without any load. A power good output open-drain logic output signals whether the output voltage is in or out of regulation. When the overload disappears, the output voltage returns to its normal value—there is no need to shut down and restart the LTC3780.

Keep Alive

LTC3780 applications often work alongside related subsystems requiring very little current. The LTC3780's
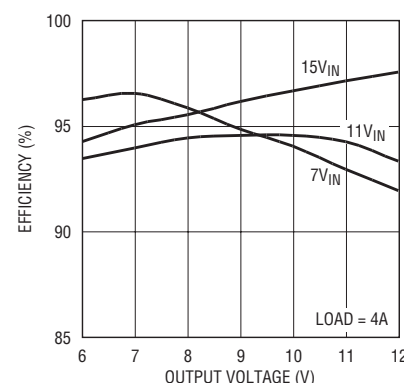

Figure 16. Efficiency for the adjustable output supply is consistently in the mid-90s.

STDBYMD pin allows the internal low dropout regulator to remain functional even when the RUN pin disables all other functions of the controller. The LDO then provides 6V at up to 40mA at the INTVCC pin for neighboring "wake-up" circuitry.

Compact, Efficient Regulator with Programmable V_{OUT}

With an external voltage applied to its V_{OSENSE} pin through a resistor, the LTC3780 can control a supply capable of providing a 4A, 6V–12V output from a 7V–15V input (Figure 15). Efficiency is in the mid-90 percent range throughout a wide range of inputs and load currents, as Figure 16 illustrates. Dual MOSFETs with integrated Schottky diodes keep the footprint to a minimum. With the application of 0.85V to 4.9V to the feedback node through a

75kΩ resistor, the output varies from 12V down to 6V. The proper external voltage can be approximated from the equation $V_{OUT} = 13.28V - 1.5(V_{REF})$. Naturally, this implementation of the LTC3780 could be applied to many other ranges of input/output voltages and currents.

Conclusion

It is not a trivial task to deliver high current with tight regulation when the input voltage can be more than, less than, or equal to the output voltage. The LTC3780's proprietary architecture shoulders the complexity and simplifies the power supply designer's job. It is the first buck-boost controller to provide extremely high efficiency, seamless transitions between operating modes, and wide input voltage range, all without resorting to cumbersome magnetics or multiple control loops.

A converter designed around the LTC3780 naturally has a wide input voltage range, which gives it unparalleled versatility. A single converter design can be powered by any of a number of rails with the high efficiency of a true synchronous buck or boost converter. Its unique advantages over common designs make the LTC3780 ideal for automotive, telecom, industrial, and battery-powered applications. *LT*

DESIGN TOOLS

Product Information

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Linear Applications Handbook, Volume II—Continues the stream of real world linear circuitry initiated by Volume I. Similar in scope to Volume I, this book covers Application Notes 40 through 54 and Design Notes 33 through 69. References and articles from non-LTC publications that we have found useful are also included.

Linear Applications Handbook, Volume III—This 976-page handbook includes Application Notes 55 through 69 and Design Notes 70 through 144. Subjects include switching regulators, measurement and control circuits, filters, video designs, interface, data converters, power products, battery chargers and CCFL inverters. An extensive subject index references circuits in Linear data sheets, design notes, application notes and *Linear Technology* magazines.

CD-ROM

The September 2005 CD-ROM contains product data sheets, application notes and Design Notes released through August of 2005. Use your browser to view product categories and select products from parametric tables or simply choose products and documents from part number, application note or design note indexes.

Brochures

Power Management & Wireless Solutions for Handheld Products — The solutions in this product selection guide solve real-life problems for cell phones, digital cameras, PDAs and other portable devices, maximizing battery run time and saving space. Circuits are shown for Li-Ion battery chargers, battery managers, USB support, system power regulation, display drivers, white LED drivers, photoflash chargers, DC/DC converters and RF PA power supply and control.

Automotive Electronic Solutions — This selection guide features high performance, high reliability solutions for a wide range of functions commonly used in today's automobiles, including telematics, infotainment systems, body electronics, engine management, safety systems and GPS navigation systems.

Industrial Signal Chain — This product selection guide highlights analog-to-digital converters, digital-to-analog converters, amplifiers, comparators, filters, voltage references, RMS-to-DC converters and silicon oscillators designed for demanding industrial applications. These precise, flexible and rugged devices feature parameters fully guaranteed over the –40°C to 85°C temperature range.

Software

SwitcherCAD™ III/LTC SPICE — LTC SwitcherCAD III is a fully functional SPICE simulator with enhancements and models to ease the simulation of switching regulators. This SPICE is a high performance circuit simulator and integrated waveform viewer, and also includes schematic capture. Our enhancements to SPICE result in much faster simulation of switching regulators than is possible with normal SPICE simulators. SwitcherCAD III includes SPICE, macromodels for 80% of LTC's switching regulators and over 200 op amp models. It also includes models of resistors, transistors and MOSFETs. With this SPICE simulator, most switching regulator waveforms can be viewed in a few minutes on a high performance PC. Circuits using op amps and transistors can also be easily simulated. Download at www.linear.com

FilterCAD™ 3.0 — FilterCAD 3.0 is a computer aided design program for creating filters with Linear Technology's filter ICs. FilterCAD is designed to help users without special expertise in filter design to design good filters with a minimum of effort. It can also help experienced filter designers achieve better results by playing "what if" with the configuration and values of various components and observing the results. With FCAD, you can design lowpass, highpass, bandpass or notch filters with a variety of responses, including Butterworth, Bessel, Chebychev, elliptic and minimum Q elliptic, plus custom responses. Download at www.linear.com

SPICE Macromodel Library — This library includes LTC op amp SPICE macromodels. The models can be used with any version of SPICE for analog circuit simulations. These models run on SwitcherCAD III/LTC SPICE.

Noise Program — This PC program allows the user to calculate circuit noise using LTC op amps, determine the best LTC op amp for a low noise application, display the noise data for LTC op amps, calculate resistor noise and calculate noise using specs for any op amp.

Databooks

Amplifiers (Book 1 of 2) —
• Operational Amplifiers

Amplifiers (Book 2 of 2) —
• Operational Amplifiers
• Instrumentation Amplifiers
• Application Specific Amplifiers

References, Filters, Comparators, Special Functions, RF & Wireless —
• Voltage References   • Special Functions
• Monolithic Filters   • RF & Wireless
• Comparators   • Optical Communications
• Oscillators

Monolithic Switching Regulators —
• Micropower Switching Regulators
• Continuous Switching Regulators

Switching Regulator Controllers (Book 1 of 2) —
• DC/DC Controllers

Switching Regulator Controllers (Book 2 of 2) —
• DC/DC Controllers
• Digital Voltage Programmers
• Off-Line AC/DC Controllers

Linear Regulators, Charge Pumps, Battery Chargers —
• Linear Regulators
• Charge Pump DC/DC Converters
• Battery Charging & Management

Hot Swap Controllers, MOSFET Drivers, Special Power Functions —
• Hot Swap Controllers
• Power Switching & MOSFET Drivers
• PCMCIA Power Controllers
• CCFL Backlight Converters
• Special Power Functions

Data Converters (Book 1 of 2) —
• Analog-to-Digital Converters

Data Converters (Book 2 of 2) —
• Analog-to-Digital Converters
• Digital-to-Analog Converters
• Switches & Multiplexers

Interface, System Monitoring & Control —
• Interface — RS232/562, RS485,
  Mixed Protocol, SMBus/I^{2}C
• System Monitoring & Control — Supervisors,
  Margining, Sequencing & Tracking Controllers

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